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AIRCRAFT WAKE VORTEX SENSING SYSTEMS

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16. Abstract

This report summarizes and analyzes techniques, both active and passive that could be used to detect and measure air movements associated with wingtip vortex generation within an area or throughout a volume of terminal airspace. This study also indicates one or more useable techniques with an appraisal of expected performance and inherent limitations. Results of preliminary feasibility tests employing available technology are presented.

This report also discusses the Systems Studies to be performed on the wake vortex sensing problem. The major effort is directed toward the location of wake vortex hazard, and the generation of monitoring requirements for safe operation in the airport terminal environment.

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TRANSPORTATION SYSTEMS CENTER

ANNUAL REPORT

GENERAL WORK AGREEMENT NO.: 71-FA-0

PROJECT PLAN AGREEMENT NO.: FA05

TITLE: Aircraft Wake Vortices Sensing Techniques

1.0 SUMMARY

PPA FA-05 defines three tasks to be accomplished in FY71. These tasks have been completed successfully. Task I and part of Task II are governed by an interdirectorate task agreement with the Technology directorate. This progress report is divided into two sections, one covering the Technology Portion and the other the Systems Studies.

1.1 Technology Effort

The Interdirectorate Task Agreement for the Technology portion of this PPA describes the task objective as follows:

"Summarizes and analyzes techniques, both active and passive that could be used to detect and measure air movements associated with wingtip vortex generation within an area or throughout a volume of terminal airspace. This study should indicate one or more useable techniques with an appraisal of expected performance and inherent limitations. Preliminary feasibility tests employing available technology shall be performed."

All of these objectives were achieved during FY71.

A preliminary survey of techniques was completed during July and August 1970. During this period it became clear that acoustic radar techniques showed considerable promise, and equipment was assembled to perform exploratory experiments. The survey and analysis were completed in November, and the required Appraisal Report was submitted on December 1, 1970. A copy of this report is attached (A).

Throughout the first half of FY71, the hardware part of the program consisted of putting together an acoustic radar system in the laboratory while constructing antennas and stands for the airport tests. In October, the first breadboard model of an

acoustic radar was successfully operated on the roof of the Technology Building, and toward the end of the month negotiations were completed with the authorities at Logan International Airport for permission to conduct experiments at the landing ends of their operational runways. A new mobile laboratory van was purchased to replace the old panel truck being used to transport equipment and personnel to Logan. With the onset of winter, field work was seriously curtailed but system improvement was continued and airport tests conducted whenever snow, wind and temperature conditions allowed. Finally, on January 19, 1971, signals were obtained with a pulsed bistatic acoustic radar that demonstrated, perhaps for the first time anywhere, that it is possible to detect aircraft wake vortices using acoustic techniques. A letter report of this observation was made to the FAA on February 10, 1971. A copy of this report is attached (B).

With the arrival of spring and the mobile laboratory van (drawing attached (C)), field testing began in earnest in accordance with item 3 of the performance schedule. During February and March data was collected at runway 33L at an increasing pace and as equipment was improved data acquisition became more reliable. The van was delivered in late March and field tests were suspended while it was being outfitted, equipped, and checked out. Early in May the acoustic range was set up in Orient Heights at the 4L localizer position, and observations were made on vortices at altitudes of 100 to 200 feet.

In May and June further advances were made in the acoustic radar and display technique. Using two receivers at different ranges, vortices are located and tracked in the plane of the radar beam. In addition, a new display was developed, showing pulse delay versus elapsed time, which records the data photographically pulse-by-pulse in real time and greatly improves the useable sensitivity and resolution of the system. Experimentation at NAFEC has now begun in earnest to ascertain the capabilities and limitations of the pulsed acoustic radar.

During the year a number of other possible sensors were examined, such as passive acoustic, pressure, and infrared.

1.2 Systems Studies

Task III of PPA FA-05 defines the Systems Studies to be performed on the wake vortex sensing problem. The goals set forth in this task have been accomplished. The major effort was directed toward the location of wake vortex hazard, and the generation of monitoring requirements for safe operation in the airport terminal environment.

Vortex transport and decay phenomena were employed to determine drift envelopes of vortices as a function of various wind conditions and runway operational configurations.

Basic models describing the motion of the trailing vortices generated by an aircraft during its landing and take-off have been formulated. These models are extensions of classical two-dimensional models (References 1, 2, and 3), and have the following unique features: the vortices do not extend to infinity in each direction, the effect of wind is included, and ground effect is not uniform along the vortices. When further refined, these models will be used to determine the wind-drift envelopes of hazardous vortices. These basic landing and take-off models are complex but are a relatively obvious first step in obtaining a description of the behavior of vortices in the vicinity of airport runways.

A computer program has been written, and numerical results have been obtained for vortices generated by a landing aircraft; an analogous program is being written for departing aircraft. The response of aircraft to a vortex encounter was examined. Simulation studies show that the intensity of the hazard is more closely related to the vortex's circulation than its core structure.

A paper entitled: "System Performance Requirements for Monitoring Trailing Vortices in a Terminal Environment" was presented at the National Aerospace Electronics Conference (NAECON) in Dayton, Ohio on May 21, 1971. The TSC authors were: M. Gorstein, J. Hallock and I. McWilliams. The scope of the runway geometry and the effects of noise abatement procedures as they pertain to the wake vortex monitoring problem were presented, using Logan Airport as a specific example.

2.0 TECHNICAL DISCUSSION

2.1 Bistatic Acoustic Radar

The scattering of acoustic waves from atmospheric turbulence is a well known phenomenon which has been proposed by a number of people as a possible means for the detection of aircraft wake turbulence. (See Attachment (D)). The Doppler shift associated with such scattering is a measure of the velocity of the wind that is transporting the turbulence. Early in our studies at TSC we became interested in a different mode of scattering, namely the refraction of the acoustic wave front by the organized motion in the core of a vortex. The cross section for this mode of scattering is much larger than that from turbulent scattering; on the other hand, it exhibits no Doppler shift arising from the vortex winds. Since Doppler scattering from turbulence is being

investigated elsewhere, we have concentrated our efforts on the detection and analysis of the very large acoustic signals available from refractive scattering.

To this end we have developed a simple bistatic acoustic radar consisting of a pulsed transmitter and a receiver located on opposite sides of the runway glide-path (figure 1). Transmit and receive transducers are mounted at the focus of identical reflectors made of plastic sheets bent to the shape of parabolic cylinders. The antennas are set with their focal axes approximately perpendicular to the ground and on the same symmetry plane, which is perpendicular to the runway. Thus, the two antennas have intersecting fan-shaped beams, and the radar is sensitive to scattering that takes place in their common volume.

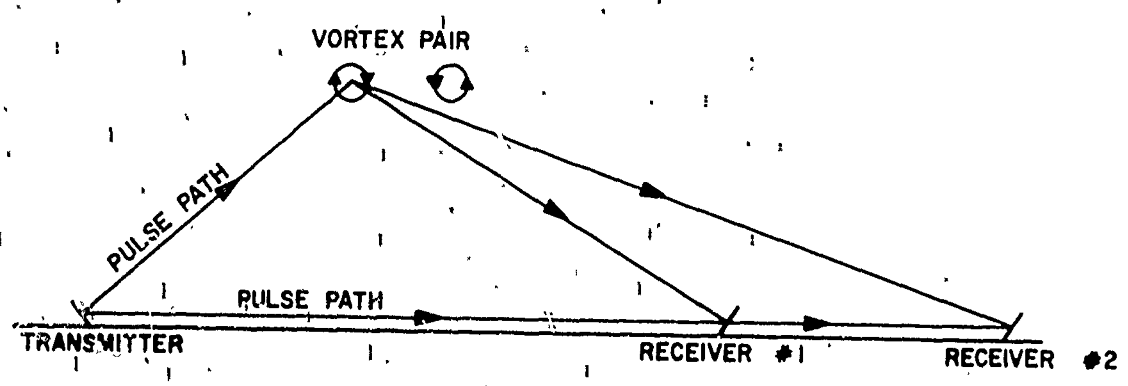


Figure 1. Pulsed Acoustic Bistatic Radar

The radar operates by transmitting short pulses of acoustic energy over a wide angle above the runway (typical pulse width is 2.5 ms at a frequency of 2.5-3 KHz with 30 watts peak power). When there are no disturbances within the sensitive volume, the receiver detects that portion of the emitted pulses which propagates parallel to the ground. The detection of these pulses provides a time reference. Whenever a landing aircraft deposits within the sensitive volume a vortex whose circulation vector

points to the left as viewed from the transmitter, then a portion of the pulse energy passing through that vortex is refracted downward and detected by the receiver. This second received pulse is delayed relative to the ground pulse by a time corresponding to the difference in path length. In this way the presence of a vortex in the sensitive volume can be detected and the vortex monitored until it decays or until it has left the sensitive volume.

A refinement of this basic system makes it possible to locate the vortex within the sensitive region and thus to determine its trajectory within that region. By adding a second receiver aligned with the first but appropriately displaced from it, one has effectively two bistatic radars with different baselines. The data is then comprised of two different time delays which are sufficient to locate the vortex and follow its motion.

The system described above has undergone extensive field testing at Logan International Airport. With the wholehearted cooperation of the Massachusetts Port Authority and FAA personnel at the airport we have been able to obtain data over a period of six months at the following sites: (Figure 2)

1. The approach end of 4R (1600 ft from the nominal threshold). These were our first field tests carried out during the winter months with primitive facilities. Also, the runway was not used as frequently as we had been led to expect. (We acquired little data but much experience.)

2. The approach end of 33L (150 ft from threshold). The first unambiguous vortex signals were obtained at this site. However, much of the data was difficult to interpret due to the low altitude at which the aircraft passed through the radar beams. This circumstance constrained us to short baselines and very small time delays, which often could not be resolved from the ground pulse. (Figure 3)

3. The middle of 33L, approximately 6000 ft from the start of take-off. Since little could be accomplished at site (2), it was decided to set up in a position suitable for the observation of take-off vortices. However, no useful data were obtained at this location during two-three weeks of tests. We attribute our lack of success to:

   a. The greatly increased noise level.

b. Equipment problems that were difficult to correct because of necessary restrictions on crossing the runway.

c. The possibly different characteristics of the wake vortex on take-off and landing.

4. The approach end of 22L (2100 ft from threshold). This location at the localizer station in Orient Heights, East Boston, gave the most consistent and best quality data yet obtained. The aircraft passed at altitudes from 100-200 ft which enabled us to use a fairly long baseline (restricted by the Government property lines). At this location a two-receiver array was used for the first time and enabled us to calculate the vortex track in the plane of the radar. Two such tracks for the left wing vortices of two different B-727 aircraft are plotted in figure 4. The inital aircraft positions shown were obtained from photographs and the vortex tracks were computed from time delay data.

   At the same location we also set up a pair of bistatic radars operating on different frequencies and propagating in opposite directions. With this two-way system we were able to obtain simultaneous tracks on both members of the vortex pair generated by a single aircraft.

   The rapid accumulation of data made possible by the facilities in the mobile laboratory van and the favorable site made it mandatory to devise a processing technique more economical of time than the laborious production of "A Scope" displays from averaged tape data. The new display scheme may be called a "vortex acoustogram" (after "ionogram"). Examples are shown in figure 5. These displays are generated by a raster scan, each vertical sweep being triggered by a single pulse. The received pulses are used to intensity modulate an oscilloscope beam so that the flat top of each pulse produces a short vertical streak on the screen and successive received pulses, horizontally displaced, trace out a record of time delay in milliseconds versus elapsed time in seconds. Such records can be produced in real time as well as from tape recordings and greatly facilitate subsequent data processing.

2.2 Passive Acoustic Sensors

The trailing vortices from many aircraft (especially those with rear-mounted engines) generate audible noise which can be

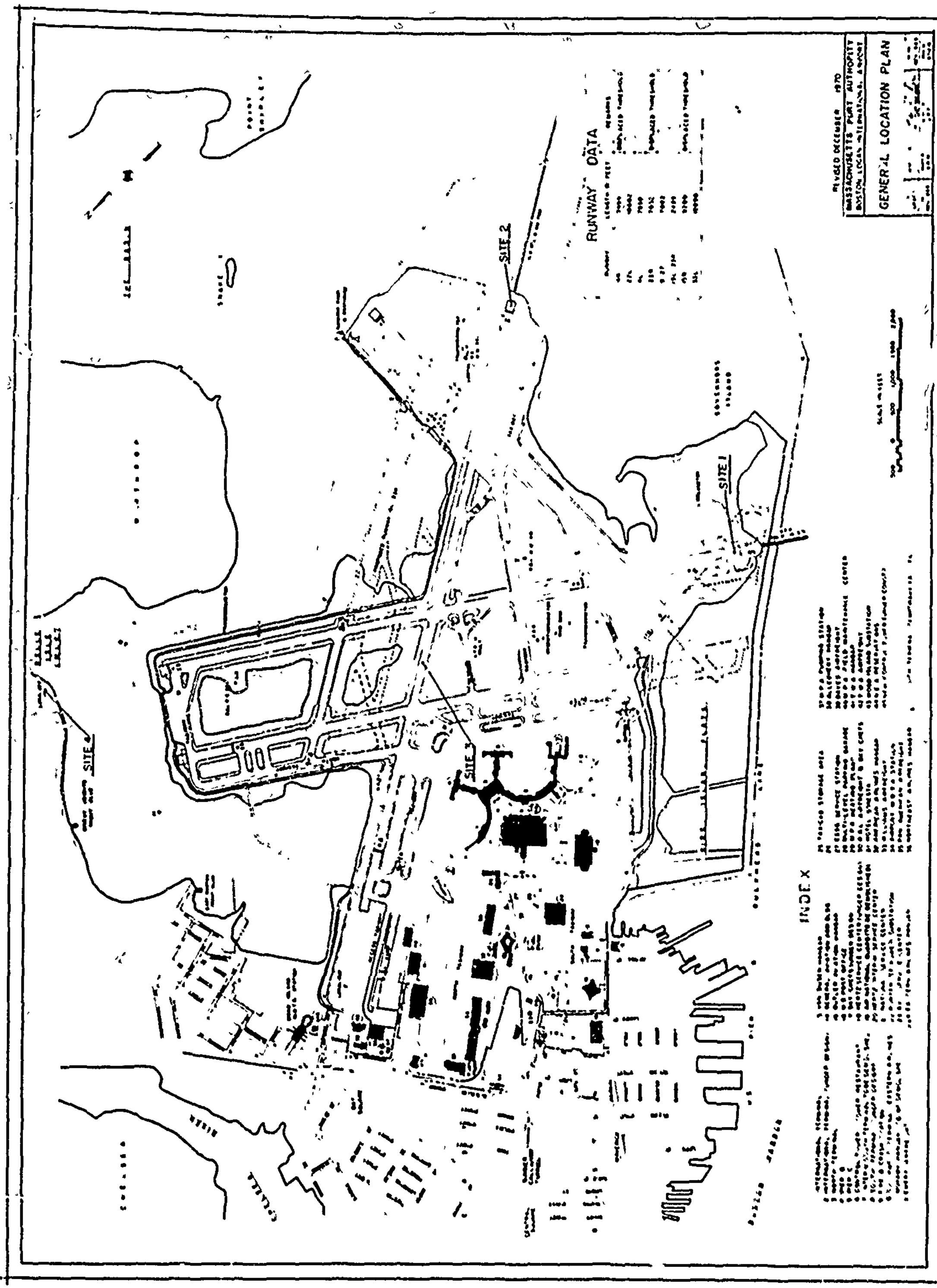
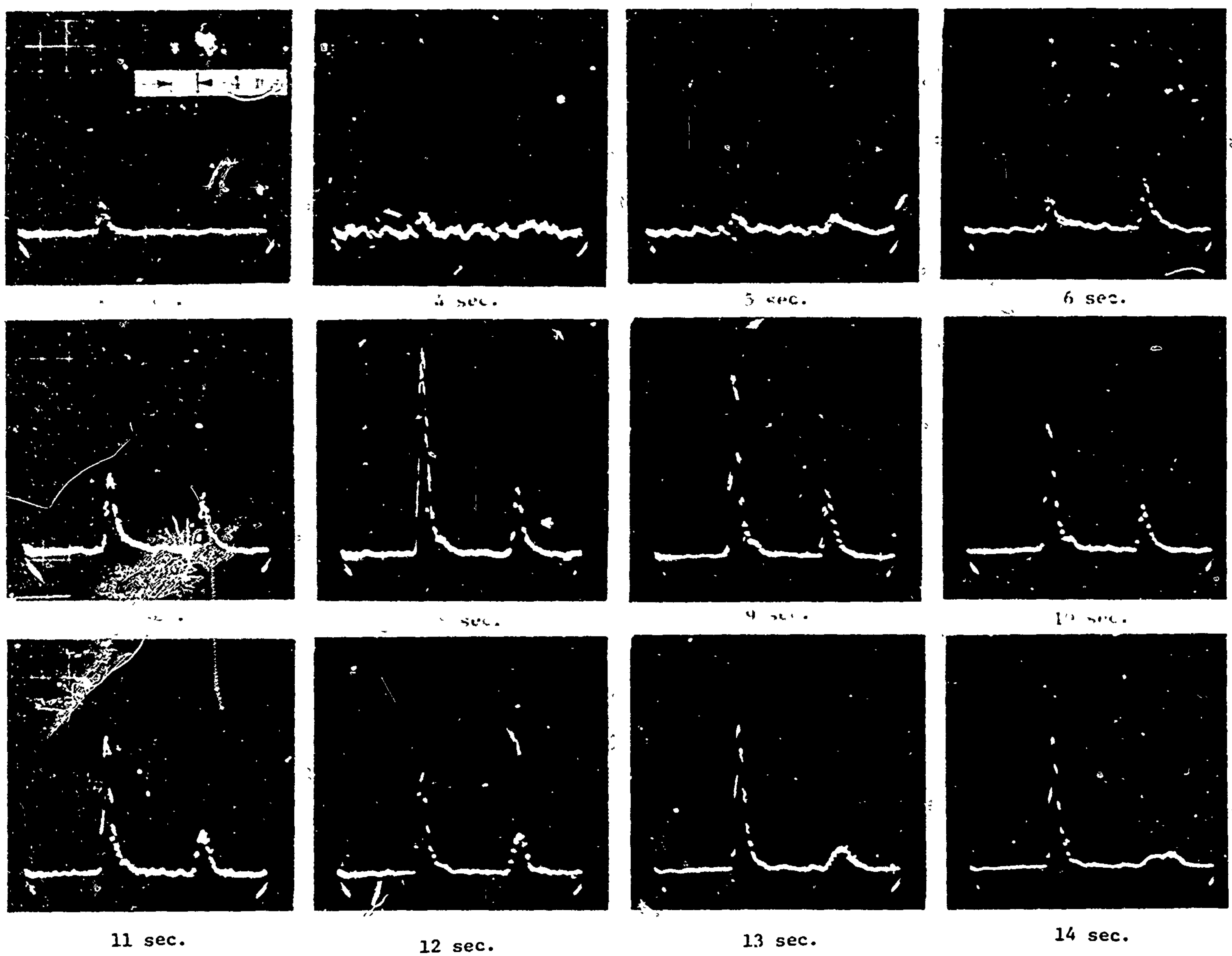


Figure 2. General Location Plan



Integration time - 1 sec. ~ 20 pulses
Pulse width - 2.5 ms
Acoustic frequency - 3 KHz

Baseline - 350 ft
Peak Power Input - 30 watts
Cross-wind component - 5 Kts

Figure 3. Bistatic Acoustic Radar Pulses Recorded During Landing Pass of a Boeing 727 Jet Aircraft

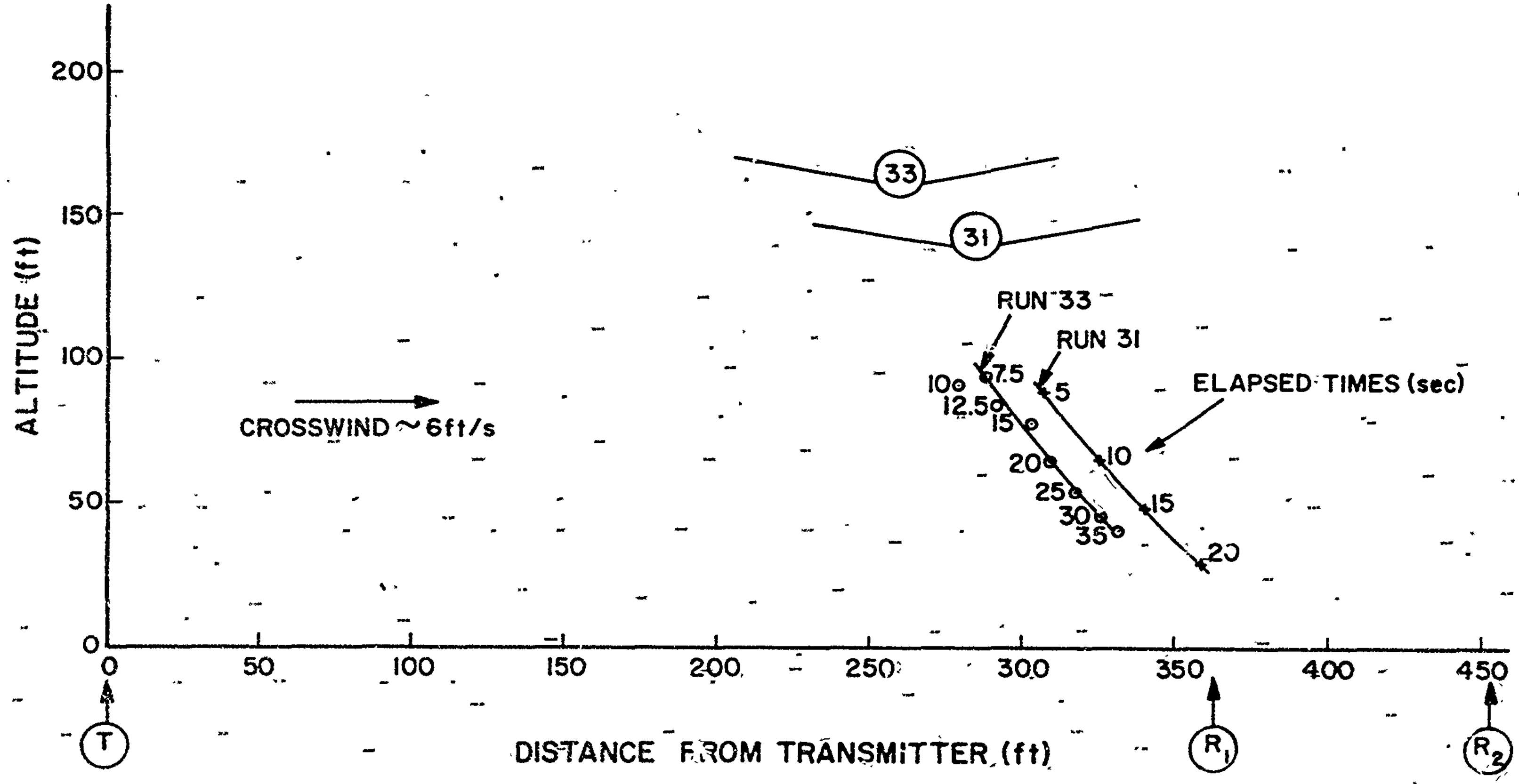


Figure 4. Left Wing Vortex - Acoustic Radar Tracks
B-727: Landing Configuration

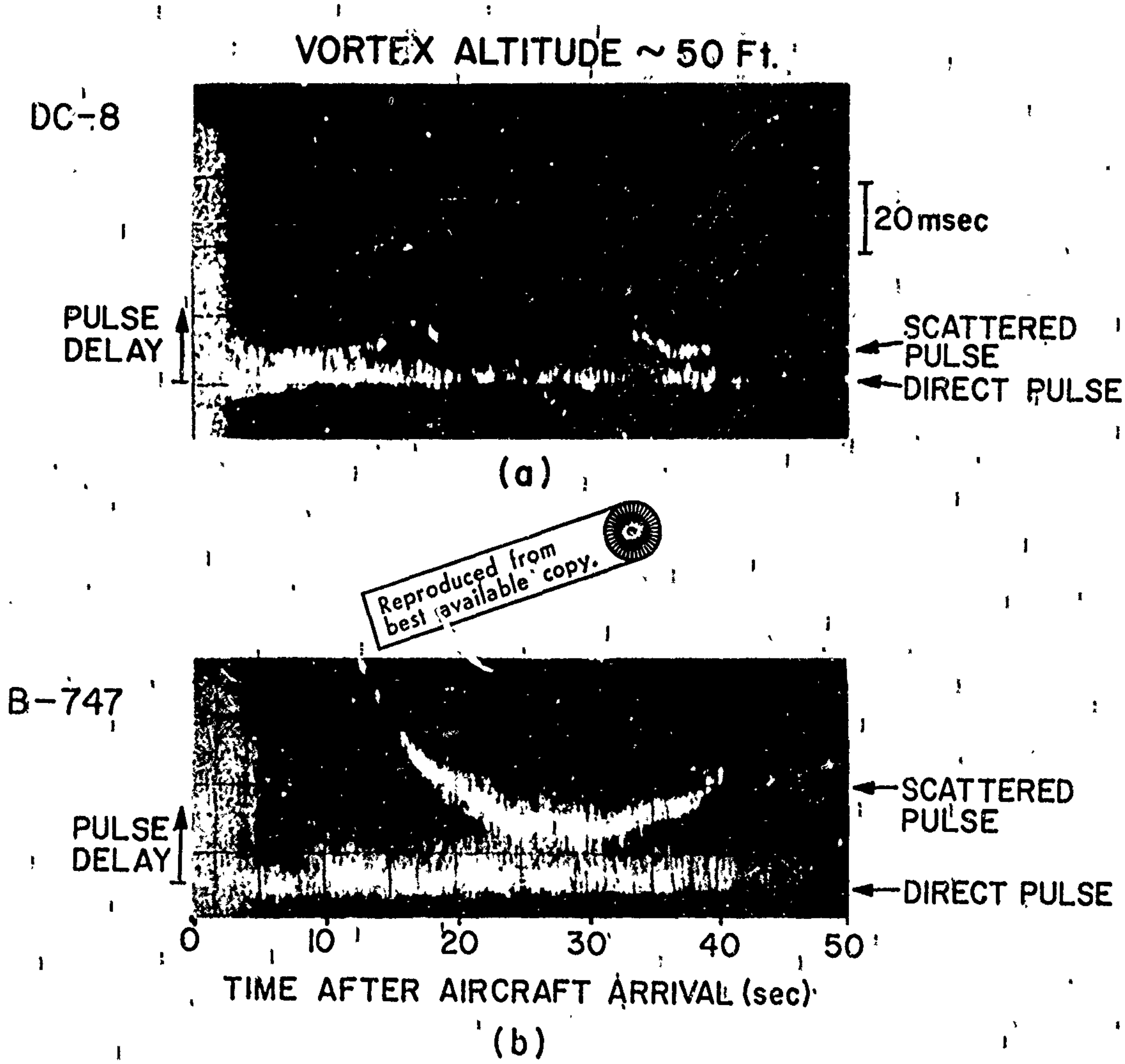


Figure 5. Vortex Pulse Delays

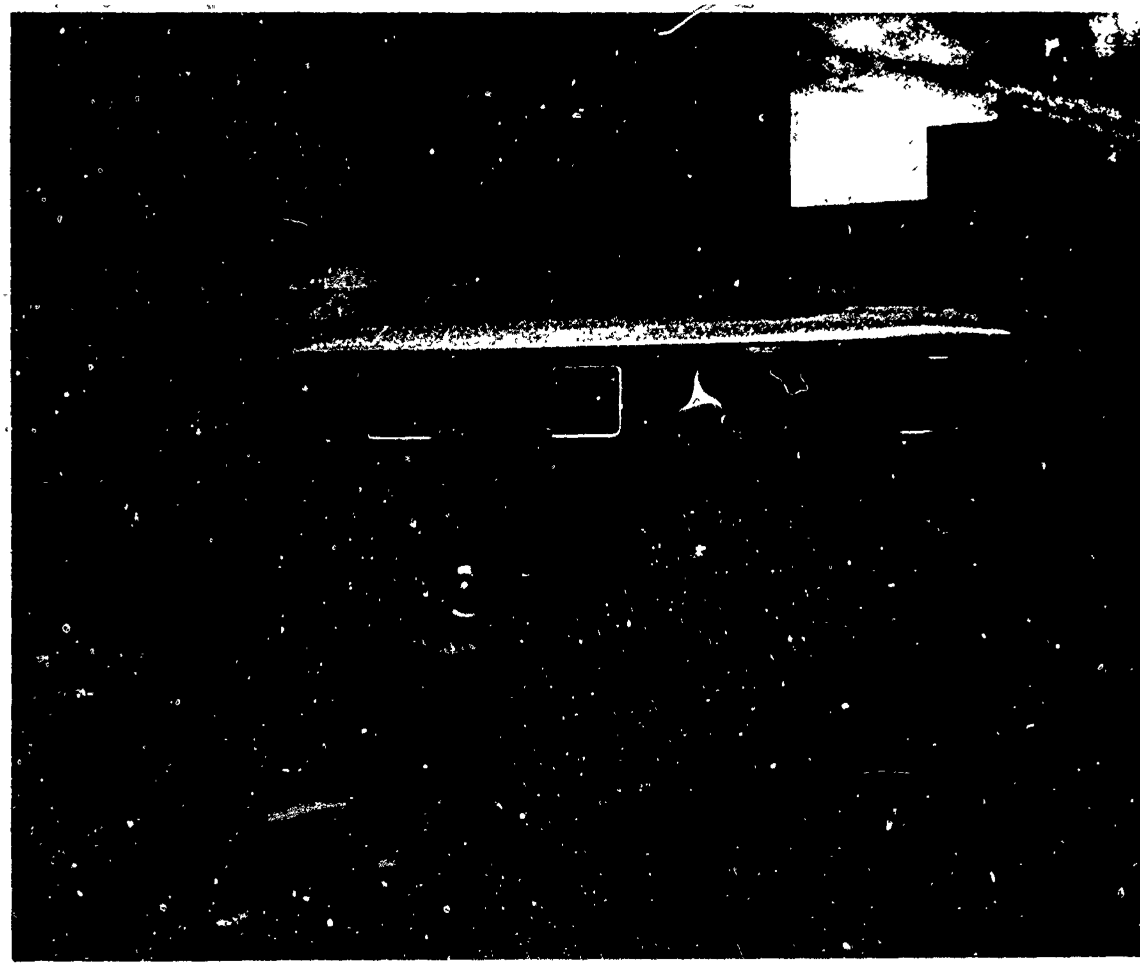


Figure 6. Mobile Laboratory

recorded and measured. A few such measurements have been made with omnidirectional acoustic transducers and with both fixed and scanning directional acoustic antennas. At short ranges the noise is readily detected, and spectral analysis shows that it is spread over a band of frequencies from 1-5 KHz.

The presence of heard sounds and felt winds on the ground suggests that other passive devices such as pressure and/or velocity sensors may be able to detect the passage of strong vortices near the ground. In a recent invention disclosure, we have suggested that an array of two or more directional passive sensors of this kind could be used to locate and monitor early vortices.

2.3 Passive Infrared Sensors

It is possible that the heat injected into the trailing vortices of aircraft with wing-mounted engines may persist long enough to permit the location of these vortices by means of the infrared radiation they emit. It appears that the CO_2 and H_2O emission bands between 4 and 7 μm are the most promising spectral regions for the short range detection of such temperature differences. A single attempt has been made to observe vortices in this way using a demonstration model of an infrared camera sensitive to radiation in the 3.5 to 6.0 μm range. At a range of 3,000 feet it was possible to see the exhaust plumes immediately behind the aircraft, but the vortices were not visible. In the near future we hope to try a simpler scanning IR system which will be constructed in our own laboratory for use at much shorter ranges (100-300 ft).

2.4 Conclusions and Recommendations

During the past year our principal effort with respect to Task I of the PPA has been to develop an operating acoustic sensor for the remote detection and location of the trailing vortex system generated by aircraft in the terminal region. This effort has resulted in a working pulsed acoustic radar which senses effects produced by the organized motion of a vortex and which locates the vortex by means of an elementary two-receiver array. Such a radar cannot directly measure tangential velocities in the vortex core as it is claimed that a CW Doppler system using turbulent scattering can do. The following table is designed to help determine the relative advantages and disadvantageous of these two alternatives.

Acoustic Radar Characteristics

	Vortex Refraction	Turbulent Scattering
Transmitter	One or two speakers with fixed fan beams, depending on need to monitor one or both vortices.	Multiple speaker array with phasing to scan volume of interest.
Receiver	At least two fixed directional microphones to locate each vortex.	Large multiple beam antenna with 8-12 microphones.
Data Processing	Pulse amplitude detection, time delay measurement, coordinate conversion.	Filter bank or spectrum analyzer for each microphone; switching and sampling circuits.
Vortex Location	Precision determined by accuracy of time delay measurement. Probably better than a vortex diameter. Absolute error does not increase with altitude within range of the radar.	Precision determined by fixed beam angles and receiver beam separation. Deteriorates as range increases and sensitive volume becomes larger.
Tangential Velocity	Not measurable.	Doppler system measures only one component of velocity. Derivation of absolute magnitude requires data as to location (see above).

It is clear from this table that the turbulent scattering technique is much more complex, therefore more costly and difficult to maintain, than the vortex refraction technique. The latter technique, on the other hand, cannot determine the tangential velocities in the vortex. The question that needs to be answered, therefore, is how much is one willing to invest to obtain this additional piece of information?

One important aspect of this question is the fact that any vortex of interest has been generated by a known aircraft in a known flight configuration. For this reason, it is known at the outset whether the vortex constitutes a hazard for the following aircraft. If so, it is safe to assume that the hazard exists

for as long as the organized flow pattern of the vortex persists. When this flow pattern is broken up, the vortex and the hazard rapidly disappear. Thus, to determine whether a hazard exists it is only necessary to know the two aircraft involved. If it is determined that a hazard exists, it is only necessary to track it until it has dissipated (no further circulation) or until it has moved out of a predetermined volume. This the pulsed acoustic radar can do with precision, as has been and will be further demonstrated at Logan and at NAFEC. Together with a few pressure or velocity sensors on the ground to track low altitude movements between runways, it may meet all the sensor requirements for a satisfactory and reliable airport system.

2.5 Computer Modeling

The landing approach model assumes the aircraft's approach to the runway is a straight line of fixed inclination to the horizontal. The vortex filaments are considered to be potential line vortices. The motion of the vortices is obtained by using the Biot-Savart law and the method of images. The program calculates the position vector, as a function of time, of a predetermined number of points on each filament. The filaments are assumed to be straight lines between these points. The self-induction of each vortex is neglected in the basic model. The effect of wind is included. An automatic plotting routine provides graphical output. Sample data are shown in Figure 7.

Figures 7 and 8 are sample output data from the vortex motion program. These data are for a Boeing 747 jet landing with a velocity of 240 ft-sec^{-1} at a flight angle of 3° to the horizontal; wind is absent. Note that the ordinate scale has been stretched in each figure and that the runway width in Figure 7 is not to scale.

Figure 7 is a top view of the runway and the vortex problem. Each symmetric pair of curves represents the location of the trailing vortices at thirty-second intervals; the vortex pair most nearly parallel with the runway corresponds to the location of the vortices at the instant of landing. The presence of wind would result in a translation and a rotation of the pattern. The numerical description provided by Figure 7 is believed to be reliable in the regions of the pattern where the vortex lines are smooth curves (out of ground effect).

Figure 8 is a side view of the runway and the vortex pattern. Only the right member of each vortex pair is shown. Again, the location of the vortices are shown at thirty-second intervals, and the upper vortex line at the left of the figure corresponds to the location of the vortex at the instant of landing. Although, some clarity is lost by overlaying the vor-

tex lines corresponding to different intervals, this representation does provide an indication of the rate of growth of the instabilities introduced by penetration into ground effect. The description of the vortices in the region inside ground effect (just over the end of the runway) is not accurate in detail. However, the fact that the instabilities are confirmed in the ground effect region is of substantial significance.

Several contributions to the theoretical literature, most of them quite recent (References 4-7), affect the refinement of the models. Review of these papers is continuing. Judgment concerning refinements to the models is also based on numerical results obtained from the basic landing model. Some tentative conclusions from these data are as follows:

1. The motion and endurance of sections of the vortices initially generated out of ground effect (higher than approximately one wingspan above the runway) can be described by relatively straight-forward application of available methods if micrometeorological conditions are sufficiently stable.

2. The description of the behavior of sections of the vortices initially generated in ground effect is much more difficult. However, instabilities in the ground effect region do not propagate out of this region in a time comparable to the time scale of the instabilities in the out of ground effect region.

It is anticipated that at the next level of refinement the landing and take-off models will include the presence of viscosity, self-induction, core structure, and an instability triggering subroutine. The final level of refinement will probably include semi-empirical decay data obtained from flight tests.

2.6 Aircraft Vortex Entry Simulation

A computer simulation of aircraft roll dynamics has been programmed. Coupled with a vortex model, the simulation determines aircraft roll as it enters and passes through a vortex. Aircraft velocity is constant and the flight path through the vortex is a straight line which can be specified a priori. Thus the aircraft can be programmed to pass through the core or above or below it etc.

At each point in time the total aerodynamic moment applied to the aircraft is calculated via an integration of the lift distribution over the wing. This torque yields the roll acceleration which is integrated twice to obtain roll angle. In this manner the entire roll history is determined as a function of time.

Although the program is a very crude simulation of aircraft dynamics, it should give some indication of the most critical parameter values and should yield insight into the problem.

2.7 Monitoring Requirement Studies

The use of a simplified model of the vortex transport using the Biot-Savart Law and image vortices below the ground plane combined with a decay curve taken from McGowen* were used to generate vortex drift envelopes and monitoring requirements for Logan International Airport. The results of these studies were presented at NAECON in May 1970 and are in Appendix I.

When airport operations are considered in the vortex monitoring system, certain salient points arise. In the present case, Logan International was chosen as the model. Logan has in operation abatement procedures which modify what would be the natural choice of runways under a variety of wind conditions.

Consider Operations on Runway 15R. The effect of noise abatement procedures on the vortex drift envelope is shown in Figure 7 of the Appendix. Wind vectors with magnitudes less than 15 knots and lying between 30° and 80° will increase the frequency of vortex crossing of adjacent runway (15L) from 1.3% to 11% as calculated from the Logan wind rose data. Combining these drift envelopes with the latest touchdown and earliest rotation points of 15R will generate the monitor areas for safe operation of aircraft on runway 15L as Figure 9 shows in the Appendix.

*Reference 8

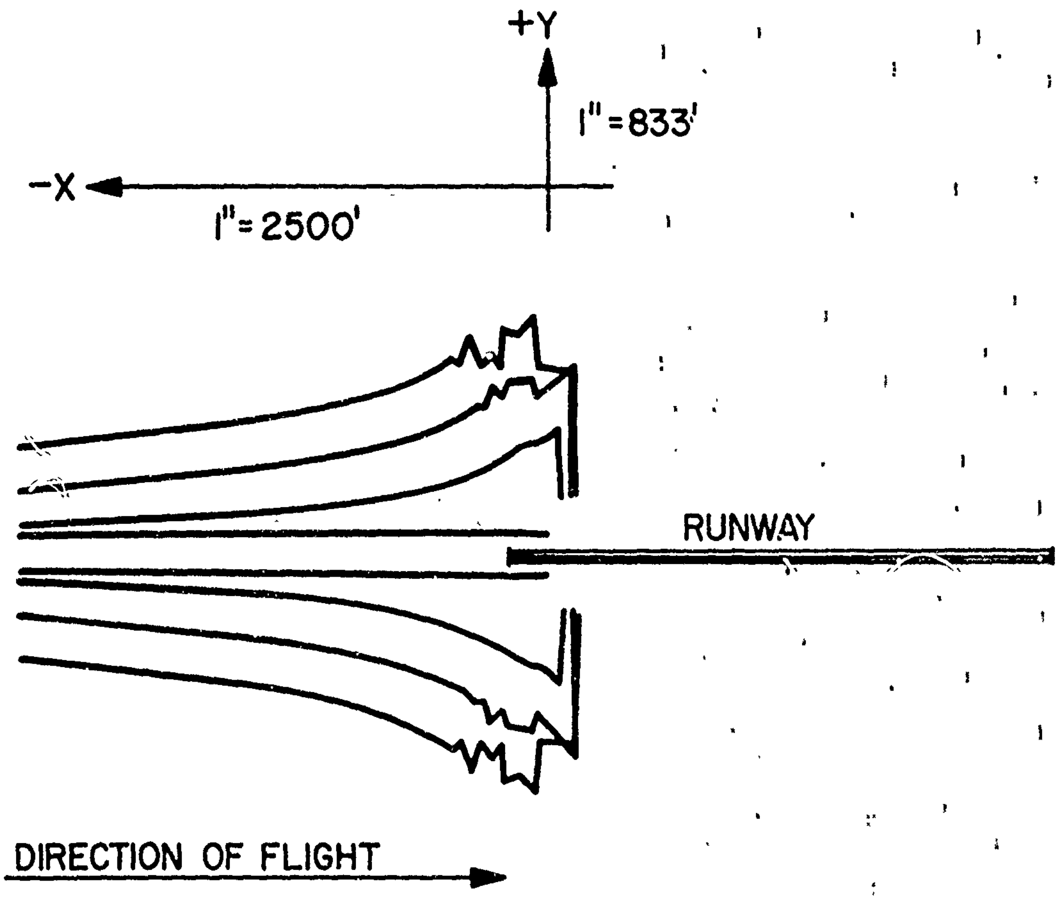


Figure 7. Top View of Vortices at 30 Second Intervals

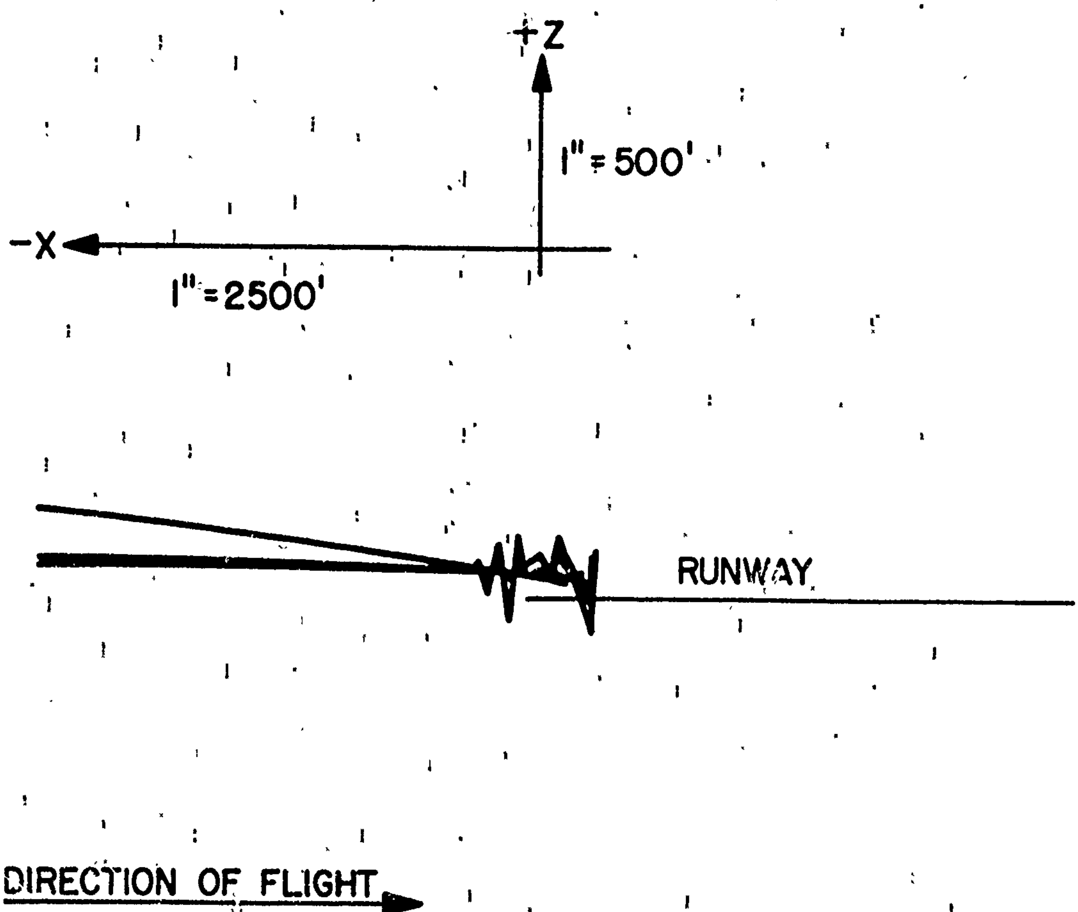


Figure 8. Side View of Vortices at 30 Second Intervals

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ATTACHMENT A

VORTEX SENSING TECHNIQUES

PPA No. FA-05

Appraisal Report - December 1, 1970

The first part of Task I of PPA No. FA-05 calls for a survey of techniques, both active and passive, that could be used to detect and measure air movements associated with wing tip vortex generation by aircraft. This survey, and a brief appraisal is contained in the following report, which concentrates primarily on ground-based-techniques that might provide a means for the remote sensing of aircraft generated vortices.

All remote techniques must depend on electromagnetic or mechanical effects produced or induced by the vortex. To be useful, such effects must accompany every vortex of sufficient strength and must endure with an adequate signal-to-noise level for a time not much less than the "lifetime" of the vortex. Techniques that are designed to detect radiations produced by the vortex will be called passive. Those that detect effects induced by the vortex on radiations from other sources will be called active.

I Electromagnetic Techniques

Active or passive electromagnetic techniques for the detection of vortex patterns in air may be classified by wavelength. Wavelengths longer than about a meter are unlikely to be of much use because of the low inherent resolution and susceptibility to interference. In the centimeter (microwave) range, adequate

angular resolution becomes available with highly directive beams, and passive radiometric techniques may be able to detect temperature differences caused by hot gases entrained in the vortices. A microwave radar may be able to measure the Doppler scatter from particulate matter or the volume scatter from regions of altered refractive index. Millimeter waves are less likely to be useful because of the present lack of sensitive systems in this range. There is perhaps more reason to examine the far infrared, since entrained exhaust gases may exhibit absorption or emission spectra which could be passively detected in suitable circumstances. Finally, optical (infrared) lasers provide a means for scattering intense, coherent beams from small particles and using the Doppler-shifted return to detect and measure vortex motions. In what follows we shall try to deal with each of these possibilities in a more quantitative way.

a. Microwave, passive

A passive microwave detector depends on a radio receiver to detect and measure the incoherent radiation associated with elevated temperatures in the vortex. This radiation, in the form of broad band noise, is indistinguishable from that generated by the receiver itself and from the background radiation incident upon the antenna. Since the background radiation will be comparable to the signal, the receiving system must be very sensitive and very stable.

In practical receivers the equivalent system noise temperature may be a few hundred degrees Kelvin. This high ambient

signal, which can be reduced only at the expense of increased complexity (masers, cooled paramps, etc.), limits the minimum detectable signal to

$$(\Delta T)_{min} = \frac{T_{sys}}{\sqrt{\Delta\nu\Delta t}} , \qquad (1)$$

where $\Delta\nu$ is the rf bandwidth, and Δt is the signal integration time. For a 1 sec. integration and a 10^6 Hz bandwidth, we see that

$$T_{sys} \lesssim 10^3 (\Delta T)_{min}$$

If a vortex is 10° K warmer than the ambient air and a 10 db signal-to-noise ratio is required, then $(\Delta T)_{min} = 1°$ K. The system noise temperature must therefore be less than 1000° K, which can be achieved with well-designed crystal mixers.

Profiles measured behind high-powered jet engines on the ground indicate that the temperature decays nearly to ambient in about 200 feet. It it possible, however, that heat convected out of a vortex may be sufficiently reduced that a measureable temperature difference will persist inside the vortex for a sufficient length of time to be of interest. In practive, an array of receivers would be necessary for localization and it does not appear that a system with the necessary sensitivity and complexity is presently feasible, though it remains a future possibility. If our resources permit, a few experiments will be carried out to test these conclusions.

b. Microwave, active

A microwave radar requires that the scattered signal received from the target should be sufficiently intense to produce the required signal-to-noise ratio in the receiver. Such a system has the disadvantage of requiring sizeable amounts of rf power, but offers the advantage that resolution in both angle and range is available with a single antenna.

The received power is given by the so-called "radar equation,

$$P_r = (P_t G^2 \lambda^2 \sigma)/(64\pi^3 R^4) \qquad (2)$$

where P_r = power input to the receiver - watts

P_t = peak power radiated - watts

G = gain of the transmit-receive antenna

λ = operating wavelength of the radar

σ = total cross section for back-scattering - square meters

R = range of the scattering volume - meters

There are two possibilities to be considered:

(1) Doppler scattering from particulate matters;

(2) Volume scattering from refractive index changes.

Particle Scattering

The total scattering cross section of particles suspended in the atmosphere (aerosols) is

$$\sigma = \sum_{j=1}^{m} n_j \sigma_j \qquad (3)$$

where n_j = concentration $/m^3$ of particles in the j^{th} size range;

σ_j = average scattering cross section of particles in the j^{th} size range;

m = number of size ranges considered.

For a spherical particle of radius a_j with $a_j/\lambda << 1$. the cross section is given by Rayleigh's long wavelength approximation,

$$\sigma_j = 4 \left[\frac{n^2-1}{n^2+2}\right]\left(\frac{2\pi a_j}{\lambda}\right)^4 (\pi a_j^2), \tag{4}$$

where n is the index of refraction of the particle. An upper limit on the cross section (approximately correct if n > 2) is thus

$$\bar{\sigma}_j = 4(2\pi\bar{a}_j/\lambda)^4(\pi\bar{a}_j^2) \tag{5}$$

with $\bar{a}_j$ defined as the weighted average radius of particles in the j^{th} size range. This weighted average is computed from an empirical formula which relates particle size to concentration:*

$$\frac{dn}{dr} = cr^{-4}.$$

The desired average is given by the formula

$$\bar{a}_j = \frac{\int_{a_1}^{a_2} r \frac{dn}{dr}\, dr}{\int_{a_1}^{a_2} \frac{dn}{dr}\, dr} . \tag{6}$$

*After Junge (1963) as reproduced in the Encyclopedia of Atmospheric Sciences p. 8 (1967).

Thus for particles in the size interval (a_1, a_2) the weighted average is

$$\bar{a}_j = \frac{3}{2} a_1 a_2 \frac{a_1+a_2}{a_1^2+a_1 a_2+a_2^2}. \tag{7}$$

Using tabulated data* with formula (7), we arrive at the following:

(a_1, a_2) (μm)	.032-.10	.10-.32	.32-1.0	1.0-3.2	3.2-∞
$\bar{a}_j$ (μm)	.0445	.1396	.445	1.396	4.8
$n_j (m^{-3})$	5.8×10^9	9.4×10^8	2.9×10^7	1.0×10^6	2.9×10^4

A reasonable wavelength for back scatter calculations is $\lambda = 10^{-2}$ m (1 cm). At this wavelength the results are:

$\bar{\sigma}_j (m^2)$	1.52×10^{-32}	1.46×10^{-29}	1.52×10^{-26}	1.46×10^{-23}	5.87×10^{-21}
$n_j \bar{\sigma}_j (m^{-1})$	8.84×10^{-23}	1.37×10^{-20}	4.42×10^{-19}	1.46×10^{-17}	1.70×10^{-16}

According to (3) the total cross section is

$$\sigma = \sum n_j \sigma_j = 1.84 \times 10^{-16} (m^2/m^3).$$

The large particles contribute almost all of the available back scattering with the second largest size range yielding only 10% of the total. This fact is a direct consequence of the 6^{th} power dependence on the radius. Thus σ may well be an order of magnitude smaller if giant (5 μm) particles are not present, or larger if their concentration is ten times as great.

The power available at the terminals of the radar receiver per unit scattering volume illuminated in the vortex may now be calculated from formula (2)

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{64\pi^3 R^4} .$$

Representative values are:

$P_t = 10^5$ watts

$G = 10^4$

$\lambda = 10^{-2}$ m

$\sigma = 1.8 \times 10^{-16}\ m^2/m^3$

$R = 10^3$ m

$P_r \sim 10^{-22}$ watts/m^3

With very low noise reception, say with a cooled paramp or a maser, an operating noise temperature as low as 50° Kelvin may be achieved. With such a system, a 20 db SNR would require a minimum power input to the receiver of $(P_r)_{min} = 10^2 kTB = 10^2 x 1.4 x 10^{-23} x 5 x 10 x 10^6 \sim 7x10^{-14}$ watts total. This assumes a 1 MHz bandwidth, B. The available power is thus at least seven orders of magnitude too small. Such a large discrepancy cannot be made up easily be increasing the power and/or decreasing the wavelength, or by increased particle concentration.

We conclude that scattering from atmospheric aerosols at microwave frequencies is negligible.

<u>Refractive Index Scattering</u>

In order to estimate the expected microwave scattering from regions of altered refractive index such as a vortex wake might produce, it is necessary to re-examine the basic definition for the back scattering cross section of such a region. The appropriate formula with which to start is

$$\sigma = 4\pi R^2 |\vec{E}_{sc}(R)|^2 \tag{8}$$

where $\vec{E}_{sc}(R)$ is the scattered electric vector at a distance R from the scattering volume. Standard electromagnetic theory provides the result that from a dielectric region P the scattered field is

$$\vec{E}_{sc}(R) \sim \frac{e^{ik_o R}}{4\pi R} k_o^2 \int_V \left[\frac{\varepsilon_v(\vec{r}')}{\varepsilon_a} -1\right] \vec{E}_t(\vec{r}')e^{-ik_o(\hat{R}\cdot\vec{r}')}dV' \quad (9)$$

where $\vec{E}_t(\vec{r}')$ is the component of electric field transverse to the observation direction $\hat{R}$ at an arbitrary point $\vec{r}'$ in the vortex. For a vortex in air the relative dielectric constant at each point is represented by

$$\frac{\varepsilon_v(\vec{r}')}{\varepsilon_a} = \frac{n_v^2(\vec{r}')}{n_a^2} = \frac{(1+\Delta n_v)^2}{(1+\Delta n_a)^2}$$

where n_v and n_a are the refractive indices inside and outside the vortex. In terms of the refractive modulus,

$$N_a = (\Delta n_a) \times 10^6$$
$$N_v = (\Delta n_v) \times 10^6$$
$$N_v = N_a + \Delta N ,$$

we find that

$$\frac{\varepsilon_v(\vec{r}')}{\varepsilon_a(\vec{r}')} = 1 + 2(\Delta N) \times 10^{-6}$$

A close approximation to the electric field $\vec{E}_t$ in the vortex is the incident field, exp $ik_o(\hat{R}_1\cdot\vec{r})$, which leads to

$$10^6 \times E_{sc}(R) \sim (e^{ik_o R}/2\pi R) k_o^2 \int_V (\Delta N(r')) e^{ik_o(\hat{R}_1 - \hat{R}) \cdot \vec{r}'} dV'. \quad (10)$$

For adiabatic processes the change in refractive modulus is related to temperature changes through the formula*

$$\Delta N = 200 \ (P_o/T_o^2) \ \Delta T$$

where P_o is the atmospheric pressure in millibars and T_o is the atmospheric temperature in degrees Kelvin. With (10) and (8), we find that the cross section for backscatter is

$$10^8 \times \sigma_B = \frac{4}{\pi} \frac{P_o^2}{T_o^4} (\overline{\Delta T})^2 k_o^4 V \int C_T(\vec{\rho}) e^{-i2k_o \hat{R}_1 \cdot \vec{\rho}} dV, \quad (11)$$

where

$$C_T(\vec{\rho}) = \frac{\Delta T(\vec{r}') \Delta T(\vec{r}' + \vec{\rho})}{(\overline{\Delta T})^2}$$

is the normalized correlation function of the temperature fluctuations about ambient. In the derivation of (11) it is assumed that the wake is homogeneous, which is perhaps the case over moderately large volumes far enough from the generating aircraft. Since $C_T(\vec{\rho}) = 0$ outside V, the volume integral may be extended to infinity and recognized as the three dimensional Frouier transform, $C_T(2k_o)$, i.e. the magnitude of the "power" spectral density of the temperature increase at a spatial wavelength, $1/2\lambda_o$. Thus, refractive index backscatter could be a

*S.H. Reiger, Astron. Journ., 68, August (1963).

strong function of the radar frequency if the vortex has well-developed periodicities. For practical reasons, only small scale periodicities considerably less than 1/2 meter in spatial wavelength would be of interest, and these are more likely to have the weak wavelength dependence that is characteristic of turbulence.

In order to arrive at some idea of the expected magnitude of the back scatter cross section, let us make the further unsupported assumption that the wake is isotropic. The correlation function may then be represented by the familiar expression

$$C_T(\rho) = \exp\left(-|\rho|/L_T\right), \tag{12}$$

where L_T is the 'correlation length" for temperature. In this situation the volume integral can be evaluated approximately,

$$\int_V C_T(\rho)\, e^{-2ik_o(\hat{R}_1 \vec{\rho})}\, dV \sim \frac{2L_T^3}{[1+(2k_oL_T)^2]^2} \sim \frac{1}{8k_o^4 L_T}\, . \tag{13}$$

This result is a good approximation when $k_oL_T > 1$, which is consistent with the earlier requirement that $L_T \sim 1/2\lambda_o$. The final formula for the back scatter from a volume V of vortex wake at an average temperature ΔT above ambient is

$$\sigma_B \sim \frac{1}{2\pi} \frac{P_o^2}{T_o^4} (\overline{\Delta T})^2 \frac{V}{L_T} \times 10^{-8} \text{ sq. m.} \tag{14}$$

At atmospheric pressure $P_o \equiv 10^3$ millibars and atmospheric temperature $T_o \equiv 300°$ K,

$$\frac{1}{2\pi} \frac{P_o^2}{T_o^4} \sim 2 \times 10^{-5}. \qquad (15)$$

Taking $(\Delta T)^2 V/L_T$ to be $O(1)$, we find

$$\sigma_B \sim 2 \times 10^{-13} \text{ sq. m.} \qquad (16)$$

This value is three orders of magnitude greater than the previously calculated particle cross section, but still so small as to make the possibility of detection marginal, even with a better choice of radar parameters. On the other hand, much depends on as yet unknown wake properties. If the average temperature differential in the wake is 10° K and the correlation length is 1 cm (λ_o = 2 cm) over volumes of a cubic meter, the cross section could be a factor of 10^4 greater, which would put refractive index scattering in the realm of detectability.

For microwave detection, both active and passive, much depends on the temperature profile within the vortex and on its variation with time. If adequate S/N should prove to exist, a passive microwave system could conceivably be used to measure some of these characteristics, even though unsuited for a working installation.

c. Millimeter Waves

The millimeter wave portion of the electromagnetic spectrum would offer attractive operational features if a sufficient S/N

ratio were available in the active (radar) mode. At a wavelength of 3 mm the attenuation due to sea-level air and water vapor is less than 1 db/km, a figure which increases only to about 3 db/km in the presence of moderate rain*. At this wavelength an antenna gain of 10,000 (40 db) over isotropic may be achieved with an aperture diameter of only 10 cm. An aperture of this size has a half-power beam width of about 2°, which means that at a range of one kilometer the characteristic transverse dimension of the illuminated volume is less than 30 meters and should provide adequate resolution in terminal areas. The high beam-directivity also means that interference from and with the airport's electromagnetic envioronment would be negligible.

The principal problems associated with the use of millimeter waves are the lack of suitable power sources and of sensitive (low-noise) detectors. At present it is unlikely that a good S/N ratio can be achieved. Since future technological developments may alter this outlook, some measurements should be made in this region of the spectrum as soon as resources permit.

d. Infrared detection

As with previously discussed portions of the electromagnetic spectrum, passive radiometry in the infrared depends upon the magnitude of temperature differentials within a vortex and the time intervals over which such differentials may persist. At these shorter wavelengths (between 10-100 μm) the incremental

*M.S. Fowler and A.H. LaGrone, NSF Rpt P-37, October (1969).

black-body radiation is enhanced for a given ΔT since the brightness spectrum has its maximum in this part of the infrared for sea level temperatures in the atmosphere. The magnitude of this effect can be calculated from Planck's radiation law,

$$B(f,T) = \frac{2hf^3}{c^2} \frac{1}{\exp(hf/kT) - 1}, \tag{17}$$

where B is the brightness per unit solid angle at frequency f (Hz) of a source at temperature T (deg. K). B is measured at the receiver in watts per square meter per hertz per steradian and per deg. K. If the black body temperature is increased from T to T + ΔT, the corresponding increase in brightness at a given frequency is found to be

$$\Delta B(f,T,\Delta T) = \frac{1}{2} \frac{hf^3}{c^2} \frac{hf}{kT} \left(\frac{\Delta T}{T}\right) \operatorname{csch}^2\left(\frac{1}{2} \frac{hf}{kT}\right). \tag{18}$$

According to this formula $\Delta B \to 0$ as $f \to 0$ and $f \to \infty$. It follows that ΔB has a miximum at some frequency f'_m. Setting $d(\Delta B)/df = 0$, we find that f'_m is determined by

$$\left(\frac{1}{2} \frac{hf'_m}{kT}\right) \coth \left(\frac{1}{2} \frac{hf'_m}{kT}\right) = 2 \tag{19}$$

or

$$\frac{kf'_m}{kT} = 3.83. \tag{20}$$

This compares with the frequency f_m for maximum brightness B at a given temperature,

$$\frac{hf_m}{kT} = 2.82. \tag{21}$$

Thus, at 300° the frequency of maximum brightness is $f_m = 1.$[illegible] $\times 10^{13}$ Hz ($\lambda_m = 20$ µm), while the maximum change in brightness per unit temperature change occurs at $f'_m = 2.5 \times 10^{13}$ Hz ($\lambda'_m = 12$ µm). It appears, then, that an infrared detector designed to operate in the range 5-30 µm may have the possibility of detecting warm wake vortices.

In order to estimate the signal power that may be available, we revert to (18) and make the approximation that

$$\Delta B(f,T,\Delta T) \equiv \frac{2h}{c^2}\frac{h}{kT} f^4 e^{-hf/kT}\left(\frac{\Delta T}{T}\right). \tag{22}$$

The integrated power over the spectrum is

$$\Delta B(T,\Delta T) = \int_{f_c}^{\infty} \Delta B(f,T,\Delta)\,df \equiv \frac{2h}{c^2}\left(\frac{kT}{h}\right)^4\left(\frac{\Delta T}{T}\right)\int_{x_c}^{\infty} x^4 e^{-x} dx, \tag{23}$$

where $x_c = hf_c/kT$, and f_c is the low-frequency cut-off of the infrared detector. The result of the integration is

$$\Delta B(T,\Delta T) \equiv \frac{2h}{c^2}\left(\frac{kT}{h}\right)^4 \frac{\Delta T}{T}\, e^{-x_c}(x_c^4+4x_c^3+12x_c^2+24x_c+24). \tag{24}$$

Choosing $f_c = f_m$, $x_c = 2.82$, we find that

$$\Delta B(300°K,\Delta T) \equiv 1.5 \times 10^{-4} \text{ watts/cm}^2\text{/°K/steradian}. \tag{25}$$

It is now possible to calculate the available power for a representative example. The required data are:

IR detector area	10^{-2} cm^2
Target area	10-10^2 m^2
Target range	10^2-10^3 m
Avge. solid angle subtended	10^{-4} steradians
Avge. ΔT in vortex	10° K

Under these conditions the total available power at the receiver is $P_{tot} \equiv 1.5 \times 10^{-9}$ watts. For cooled solid state infrared detectors the noise equivalent power is typically NEP $\equiv 2 \times 10^{-11}$ watts/Hz$^{1/2}$. Thus, the signal to noise ratio could be as much as 10-20 db, depending on wake vortex characteristics such as temperature and optical depth.

Conclusions

From the above considerations it seems clear that electromagnetic techniques hold only limited promise for the remote sensing of wake vortices as they are generated by aircraft. With present technology three methods in two regions of the spectrum seem to hold some promise and should be explored.

1. Infrared laser Doppler radar. This technique has been developed and demonstrated by NASA. Although it can measure local flow velocities in vortices, it has many inherent difficulties:

(a) It is a focussed system with a resolution cell that is much too narrow in angle and long in range for

operational applications.

(b) Doppler measurements depend on the coherent interference between the scattered radiation and a reference beam. This method of detection imposes severe requirements on the stability of the optical system that may be difficult to meet and maintain in an airport environment.

(c) Optical scanning in range and angle presents many engineering difficulties.

(d) Precipitation and other hydrometeors may adversely affect the S/N ratio.

2. Infrared passive detectors. Infrared detectors of sufficient sensitivity are available and provide a reasonably good prospect for vortex sensing if even small temperature differentials exist and persist between the vortex core and the ambient atmosphere. It is still necessary to consider atmospheric effects, but suitable optics can be chosen to define any desired field of view, and previously described arraying techniques provide the means for localizing the vortex in a volume of space.

3. Microwave radar. The scattering of short electromagnetic waves from refractive index inhomogeneities in a vortex appears to be a marginal technique at best. Much depends on the temperature and pressure profiles and fluctuations within the vortex, and these must be determined before any precise feasibility estimates can be made. On a low priority basis, however,

it is probably worthwhile to set up a simple microwave radar for a quick check of the actual scattering cross sections of typical vortices. This is so because microwaves have so many potential technical advantages: moderate to negligible atmospheric effects; well-developed technology; straight-forward techniques for range and angle determination, etc.

It is clear that the proper evaluation of most of these techniques requires knowledge of the temperature and pressure profiles within the vortex, as well as of the velocity fields. Such information is also required for the proper interpretation of the data that may be obtained from any particular sensor (except perhaps for the Doppler lidar). One important step in this direction is being made at NAFEC with its proposed instrumented tower facility. Correlation of data from these towers with that obtained from remote sensors should lead to a significant advance in the understanding of vortex dynamics.

II Mechanical Techniques

Up to this point we have restricted the discussion to electromagnetic techniques. It remains to consider the only mechanical means that is suitable for remote sensing, namely acoustics. As before, both passive (listening) and active (sonar) techniques will be considered. The frequency range involved is the mid-audio, 100-10,000 Hz. At frequencies below this band the wavelength is so long that the characteristic dimensions in the vortex are too small either for the genera-

tion of significant acoustic energy or for adequate resolution. Above this frequency atmospheric absorption becomes a significant factor.

a. <u>The scattering of sound</u>

The scattering of acoustic waves in the atmosphere by a vortex may have both coherent and incoherent components, and both of these have been considered as possible means for vortex detection. Incoherent techniques have already been reduced to practice in the acoustic sounding of the atmosphere. A brief survey of the history of the subject is attached to this report. The basic formula derived by Kallistratova and used by all workers in this field is

$$d\sigma = 2\pi\kappa^4 V\cos^2\theta \frac{1}{C^2} E(K)\cos^2 \frac{1}{2}\theta + \frac{1}{4T^2}\Phi_T(K)\,d\Omega, \qquad (26)$$

where $d\sigma$ is the fraction of the incident acoustic power which is acattered by irregularities in a volume V through an angle θ into a cone of solid angle $d\Omega$, $k = 2\pi/\lambda$ is the wave number of the acoustic wave, C is the speed of sound, and T is the absolute temperature in the scattering volume. $E(K)$ and $\Phi_T(K)$ are the three dimensional spectral densities of the wind velocity and temperature fluctuations at the wave number $K = 2k \sin 1/2\ \theta$. It should be noted that for back scatter $\theta = \pi$ and

$$d\sigma(\pi) = 2\pi^4 V \frac{\Phi_T(2k)}{4T^2}\,d\Omega \qquad (27)$$

which is independent of mechanical (velocity) turbulence and depends only upon the spectral density of the temperature fluctuations in the boresight direction at half the incident acoustic wavelength. This formula presents a possible means for measuring the spectrum of temperature fluctuations within a vortex. However, calculations by Thomson* indicate that in order to achieve a S/N ratio equal to 10 db, the noise background must be less than 52 db, a level characteristic of normal conversation. Such a back catter system would be marginal at best in an airport environment.

In forward directions, the scattering given by (26) is maximized and with a Kolmogorov spectrum of turbulence, the S/N ratio may be as much as 25 db higher than the backscatter estimates. Thus, a S/N ratio of 10 or more can be achieved with a background noise of 77 db or less. This level corresponds to a fairly noisy environment such as exists in busy street traffic, for example: A forward scatter technique of this kind is presumably being developed by Xonics and others and appears to be sensitive enough to warrant further investigation.

An alternative acoustic scattering process in vortices, studied at TSC by D. Burnham, is currently being instrumented for field tests. The method involves coherent scattering by the vortex core and will be described in detail in a forthcoming

*J.A. Thomson, Draft Report, NASA Contr. No. NAS 8-24810, May (1970).

report. In summary, the theory involves ray-detection and transit time integrals that have been studied for the propagation of sound through a simple line vortex by Lindsay (1948) and through a vortex core with a radial variation of sound speed by Salant (1969). A somewhat different method of approximation leads to results that make it possible to infer the coherent scattering properties of aircraft vortices. The scattering cross sections are large, and yield calculated time delays of the order 10-100 milliseconds and scattering angles between 0.1 and 0.5 radian. It thus appears likely that a pulsed bistatic acoustic radar system would be capable of sensing the presence of a vortex of a certain strength and of showing its location.

All indications are that the scattering of acoustic waves by wake vortices should be strong enough to make it possible to detect them by this means. Both incoherent and coherent techniques are presently being investigated wither at TSC or elsewhere, and actual field data should soon be available. It will then become possible to determine whether the necessary precision and reliability can be achieved with an active acoustic system. An intriguing possibility is the use of a combination of acoustic and electromagnetic techniques that will have the sensitivity of the first and the precision of the second. Such schemes are being given active consideration by the Technology group at TSC.

b. Generation of sound

A further mechanical effect of vortices that has been remarked upon by a number of observers is that a vortex is an audible sound source with a frequency spectrum that is apparently peaked so that the noise has the subjective character of a "whine". So far this effect seems not to have been measured in a quantitative way. We expect to set up microphones for this purpose while testing our acoustic radar at Logan Airport.

Prepared by Ralph D. Kodis

ATTACHMENT B

U.S. DEPARTMENT OF TRANSPORTATION

TRANSPORTATION SYSTEMS CENTER
55 BROADWAY
CAMBRIDGE, MASSACHUSETTS 02142

DATE: February 10, 1971

REPLY TO
ATTN OF: TEC

SUBJECT: Acoustic Radar Data Record

The vortex data on the enclosed print were recorded on the afternoon of January 19, 1971 in clear weather, with a light cross-wind component directed toward the receiver of the two-terminal acoustic radar. To our best knowledge it is the first such data to be obtained anywhere and was recorded on the first occasion when the acoustic system was in operation and a landing aircraft traversed the activated beams. That event takes place at the frame captioned "0 sec." on the print.

Before that, at -7 sec. all is quiet, and the received pulses come in along the ground propagation path that crosses the end of runway 33L at Logan. The travel time along the ground is about 700 milliseconds with fluctuations of ±1 millisecond corresponding to a wind speed fluctuation of ±1 foot/sec. The small "precursor" which is seen to peak about 4 ms. before the main pulse, is the signal picked up on the back-lobe of the microphone as the pulse passes on its way to the parabolic reflector. The microphone is mounted two feet in front of the reflector, at its focus, so that the separation between the precursor and the main pulse is about what one would expect.

At -2 sec. the engine noise of the approaching aircraft begins to be picked up, and the noise level rises with consequent decrease in S/N as the aircraft passes overhead. With 2 sec averaging, however, adequate signal-to-noise is maintained. At +2 sec. the aircraft has passed out of the beam, although the noise continues to rise, and a later, after-pulse can be observed coming up with a delay time of about 12 ms. This delay indicates that scattering is taking place from a region 60-65 feet over the midline of the runway.

At +4 sec. the presumed upwind vortex signal is well-developed. The ground pulse, however, is all but wiped out in this and the next frame; which may perhaps be attributable to the disturbance of the ground path by the downwash from the aircraft. At +7 sec. the vortex signal delay has decreased to 9 ms., indicating a decrease in height to about 55 feet, where the vortex appears to remain with decaying strength until +12 sec.

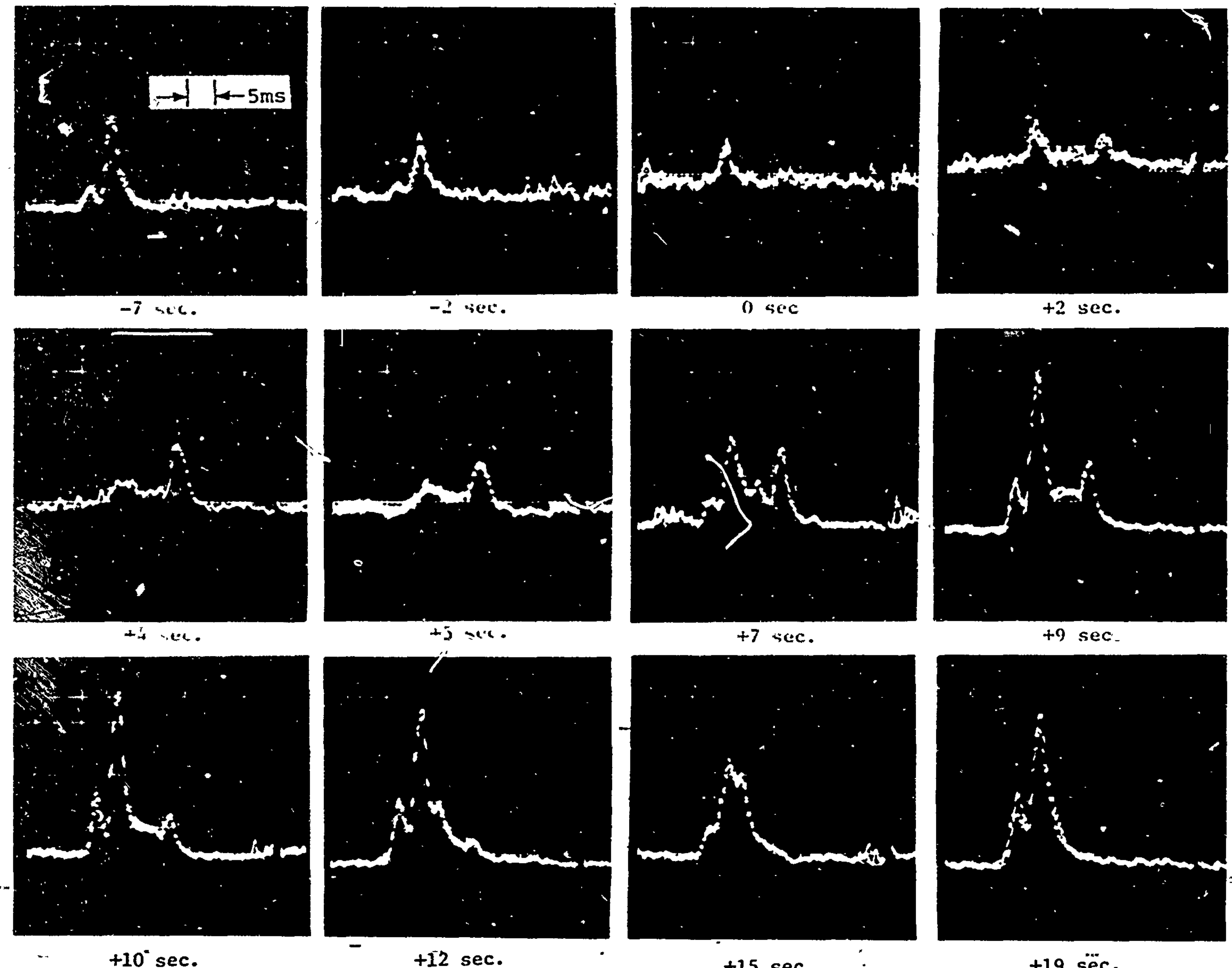
At this time another small signal can be discerned about 3.5 ms. after the ground pulse. The signal is still present at +15 sec. with a delay of 2 ms. The correct interpretation of this feature is not yet clear, but it could be associated with the near (downwind) vortex. This explanation would require that vortex to have settled much closer to the ground (25-35 feet) so that the scattering angle would be sufficiently small to account for both the presence of the signal and the short delay time.

At +19 sec. the baseline and ground pulse have returned to their quiescent values.

Subsequent recordings of the wakes of heavier aircraft exhibit features similar to those described above.

Bistatic Acoustic Radar Pulses Recorded during Landing Pass of a

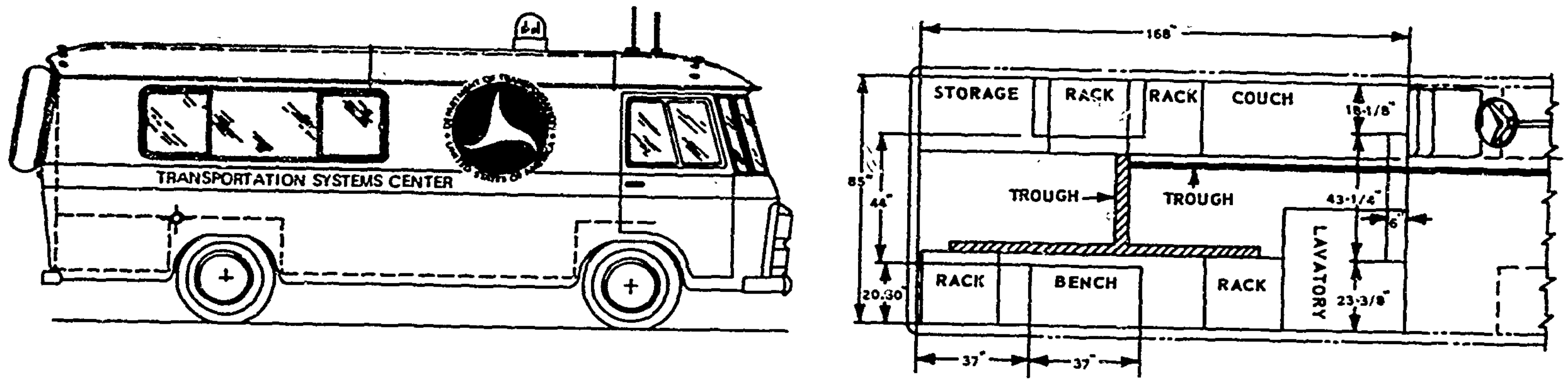
Twin Engine Propeller Driven Aircraft

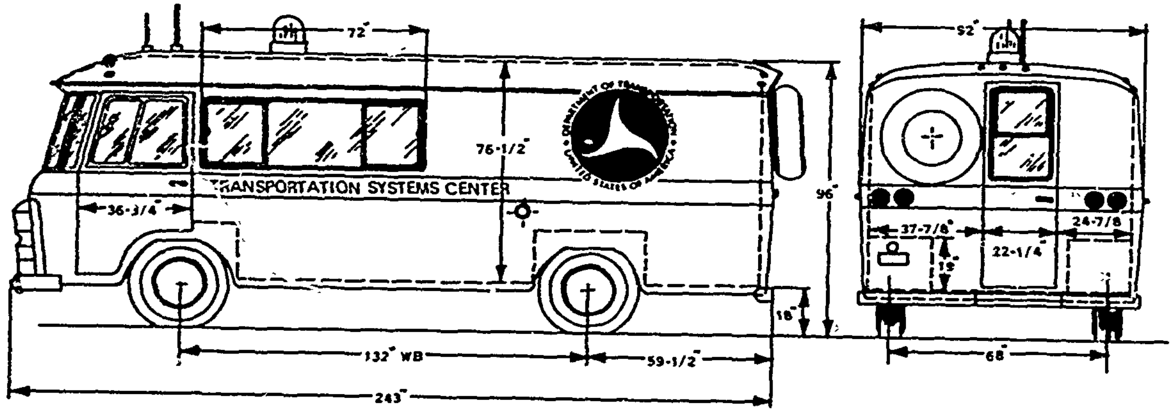


Integration time - 2 sec. ~ 40 pulses
Pulse width - ~2.5 ms
Acoustic frequency - 3 KHz

Cross Runway Baseline - 700 ft.
Peak Power Input to Radiator - 30 watts

ATTACHMENT C





MAX. PERMISSIBLE LOADED WEIGHT (INCL. PASS.)

FRONT AXLE	5500#	2750# EACH WHEEL
REAR AXLE	5500#	2750# EACH WHEEL

TOTAL GVW 11,000#

ATTACHMENT D

U.S. DEPARTMENT OF TRANSPORTATION

TRANSPORTATION SYSTEMS CENTER
55 BROADWAY
CAMBRIDGE, MASSACHUSETTS 02142

DATE: November 19, 1970

REPLY TO
ATTN OF: TEC

SUBJECT: Information Background on Vortex Sensing by Acoustic Radar

The observation that sound waves are scattered by irregularities in the atmosphere was made at least as early as 1946 at the Bell Telephone Laboratories[1] when high-intensity acoustic echoes were observed from the lower levels of the troposphere. The theory of the phenomena was tested experimentally by Kallistratova[2,3] from 1959-1961. Kelton and Bricout[4] showed in 1964 that acoustic Doppler measurements of wind velocity could be made, and McAllister[5,6] demonstrated in 1968-9 that echoes could be obtained from a turbulent atmosphere using a pulsed acoustic radar at 1000 Hz with 15 watts of radiated power. Data were obtained and studied over a height range from 25 to 300 meters.

A paper reviewing the potential usefulness of acoustic methods for the remote probing of irregularities in the lower atmosphere was presented by Little[7] in 1968 at the Scientific Meetings of the Panel on Remote Atmospheric Probing to a Committee of the National Academy of Sciences. This presentation was published in 1969 as a paper in the IEEE Special Issue on Remote Environmental Sensing[8]. Among the concluding sections of that paper is the statement that acoustic echo-sounding techniques could be developed to measure up to heights of 1500 meters the vertical profile of wind speed and direction using the Doppler technique. "In particular, the author suggests that active consideration be given to its application to... such airport problems as <u>the measurement of low-level wind shear and the detection of wake turbulence</u>". (italics added)

Subsequently in May of 1970, this suggestion was acknowledged and considered for NASA by J. A. Thomson of Wayne State University[9]. As a result of specific calculations he also concludes that "the sensitivity of this nonoptimized forward scatter system appears high enough that further investigation (of vortex turbulence) is warranted".

We in TEC were aware of these possibilities by mid-July, shortly after we had begun to look into the technical problem for the FAA. By early August, we were well along with our plan for an acoustic experiment. It was not until August 31 that we were informed by William Gough (FAA) of the Xonics experiments. Their approach seemed to us to be somewhat different and we continued with our efforts to acquire technical competence and operational experience with this and other techniques

for vortex sensing. It seems clear that almost all the relevant technical information in this field is in the public domain and is available to anyone who wants to work on the problem.

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[9]J. A. Thomson, "Study of the operational feasibility of Doppler detection systems," NASA Contract No. NAS 8-24810, May, 1970.

ATTACHMENT E

ABSTRACT

SYSTEM PERFORMANCE REQUIREMENTS FOR MONITORING TRAILING VORTICES IN A TERMINAL ENVIRONMENT

By

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And

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It has been suggested* that capacity increases at new and retro-fitted airports can be achieved primarily by increasing runway utilization rates, reducing separations between aircraft in the approach and departure zones, and by closer spacing of parallel runways on the surface.

The frequency of occurance of hazardous encounters between aircraft operating in the terminal area and wing tip trailing vortices shed by other aircraft can be expected to increase with the latter two changes unless: 1) some mechanism can be found for inducing reliable, rapid vortex dissipation or 2) the location and intensity of trailing vortices in the terminal area can be sensed and the information used in controlling aircraft.

This paper discusses the latter approach to the wake turbulence problem. Monitoring as a solution to the wake turbulence problem depends upon several characteristics of the trailing vortices themselves. First, the hazard is localized into two horizontal tornado-like cylinders whose significant peripheral velocities are contained within radii of approximately 75-100 feet. Second, the vortices do not persist indefinitely but decay due to viscous diffusion or break apart due to vortex instabilities. Third, vortices are not stationary, but move vertically and laterally due to the combined effects of wind, mutual induction, and ground effects. These three factors combine to make aircraft-vortex encounters unlikely with present separation standards. Even with decreased separation standards, frequency of occurance of vortex encounters can be shown to be

*Report of the DOT ATC Advisory Committee, December, 1969.

small. However, these factors enhance the effectiveness of monitoring as a solution to the wake turbulence problem provided that reliable and efficient means for sensing the location of hazardous trailing vortices can be found.

Vortex monitoring can be separated into three situations. These are, (1) in the approach and departure corridors due to preceding aircraft; (2) between adjacent runways, i.e., between parallel runways, between open V-type runways, between a main runway and a VTOL, STOL or general aviation runway; (3) at runway intersections from wakes generated by aircraft using the intersecting runway or to permit take-offs from runway intersections or taxiways.

The paper will discuss the performance requirements for systems capable of monitoring trailing vortices for these situations. The monitoring requirements are shown to depend upon the vortex characteristics, the airport-runway geometry, the operational characteristics of the airport (separation standards, runway usage and runway selection as a function of wind vector). The significance of these factors are discussed and examples are given for several vortex monitoring situations at Logan Airport in Boston. Based on local wind rose data at Logan, the frequency of occurance of the hazards are also examined.

FIGURE 1 is a plot of vortex lifetime as a function of ambient wind speed. Vortex lifetime is defined as the time necessary for the maximum tangential velocity in the vortex to fall below some arbitrary cutoff value (in this case 15 ft/sec). It is seen that the points extrapolated from the CV 880 data taken at NAFEC fall below the published curve of McGowan.

FIGURE 2 shows the locus of maximum vortex drift for a B-747 obtained from a computer program that includes mutual induction, ground effect and winds when the wind vector varies from zero to 35 mph and from directly down the runway to 80 degrees to either side. Two initial vortex generating heights are shown, h = 50 feet and h = 250 feet. This figure shows how the maximum drift envelope varies in extent for small changes in aircraft height. For our studies, we have assumed the maximum extent of the vortex is that obtained at a generating height of 50 feet using the McGowan endurance curve.

FIGURE 3

If the maximum drift envelope corresponding to an altitude of 50 feet is superimposed at the approximate touchdown and rotation points of runway 15R/33L at Logan Airport, Figure 5 is obtained. This figure shows the maximum lateral extent to which operations on Runway 15R/33L can affect following traffic on the same or other runways.

FIGURE 4

For take-off, runway selection is shown as a function of wind vector on Figure 4. For landings and take offs, the runway which minimizes the cross wind component is usually selected. At Logan Airport, additional procedures are taken for noise abatement purposes. The anti-noise procedures in use at Logan are defined in Control Tower Bulletin 68-1 which lists the order of priority to be used in assigning runways. These priorities affect primarily the choice of runway for take offs. For landings, all runways have equal priority except runway 22R which is to be used last. Controllers are told to assign runways in the following order beginning with the most desirable: 15R, 9, 22R or 22L, 4R, 33L, 27, 4L. Runways are used in this order provided (1) the crosswind does not exceed 80 degrees (2) the wind velocity does not exceed 15 knots (3) the runway is clear of any conditions which make its use unsuitable.

The figure shows the order of priorities and the corresponding wind vector conditions. Above a wind speed of 15 knots (17.3 MPH) the geometric minimum cross wind runway is used.

FIGURE 5

A polar plot of the wind vector conditions which cause the vortices to remain within ±150 feet of the runway center-line for aircraft separation times greater than 120 seconds is shown. These conditions vary with the aircraft separation interval, aircraft altitude and the distance from the runway centerline assumed to constitute a hazard.

For the case shown, the left vortex is carried safely beyond the hazard threshold in 120 seconds with zero cross wind. If the crosswind velocity is approximately 3.9 miles/hour, the vortex will be centered over the runway at 120 seconds. This is represented by the solid line in the center of the shaded regions. If the cross wind velocity is greater than this value, the vortex will drift across the runway. The crosswind velocities corresponding to the vortices reaching the left and right hazard distances (+150 feet) in 120 seconds are the inner and outer boundaries of the shaded regions.

FIGURE 6

Figure 6 presents the frequency with which the B-747 vortex axis will lie within 75 or 150 feet of the center of runway 15R for an initial vortex height of 100 feet. The data is presented as a function of the aircraft separation interval for wind heading limits of ±30 and ±80 degrees. The latter corresponds to the noise abatement procedures currently in use at Logan. From the graph, one can see the significance of noise abatement priority restrictions on the frequency of occurence of the vortex hazard.

FIGURE 7

This shows the drift envelope for an element of the left vortex of a B-747 aircraft operating at 100 feet altitude assuming the vortex lifetime data presented previously. The wind vector is assumed to lie within the envelope in the upper right hand portion of the figure.

Superimposed on the figure to proper scale are runways 15L and 15R at Logan Airport. From the figure, one can determine the wind vector conditions causing a vortex to drift from runway 15R and cross runway 15L.

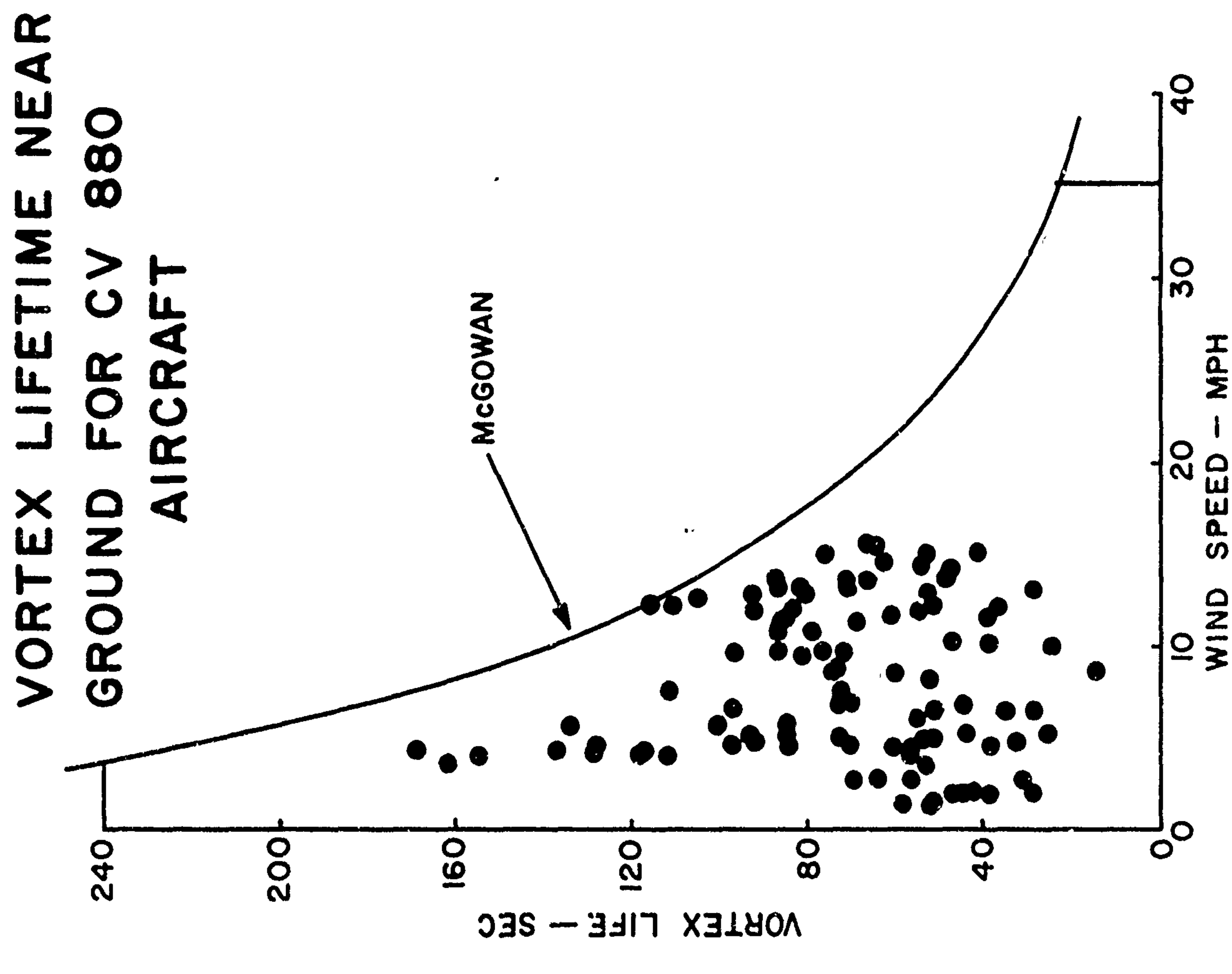
FIGURE 8

If these wind conditions causing a vortex to drift from runways 15R over onto runway 15L are plotted on a polar diagram, Figure 8 is obtained. The frequency of occurence of the wind condition can be obtained from the wind rose data. The significance of the noise abatement procedures on vortex hazard is shown by the dramatic increase in the frequency of occurence from 1.3% for the 30^{o} limit to 11% for the 80^{o} limit.

FIGURE 9

Figure 9 shows the geometry of runways 15L and 15R. The runways are separated by 1500 feet.

In order to define the monitoring areas, the operations of aircraft traffic on both runways must be considered. For our studies, we have assumed that the latest touchdown for jet traffic landing on 15R will occur 1500 feet from the runway threshold and the earliest rotation point will occur at a distance of 4500 feet from the runway threshold. These points are indicated on Figure 9 by the two aircraft silhouettes. These points define the extreme (latest and earliest) points at which vortices will be generated, and the locus of vortex decay for these two points are shown by the shaded regions. To reach these regions, the vortices must travel through the hatched regions which are the regions for vortex monitoring.



VORTEX LIFETIME NEAR GROUND FOR CV 880 AIRCRAFT
McGOWAN
VORTEX LIFE — SEC
240
200
160
120
80
40
0
0
10
20
30
40
WIND SPEED — MPH

Figure 1.

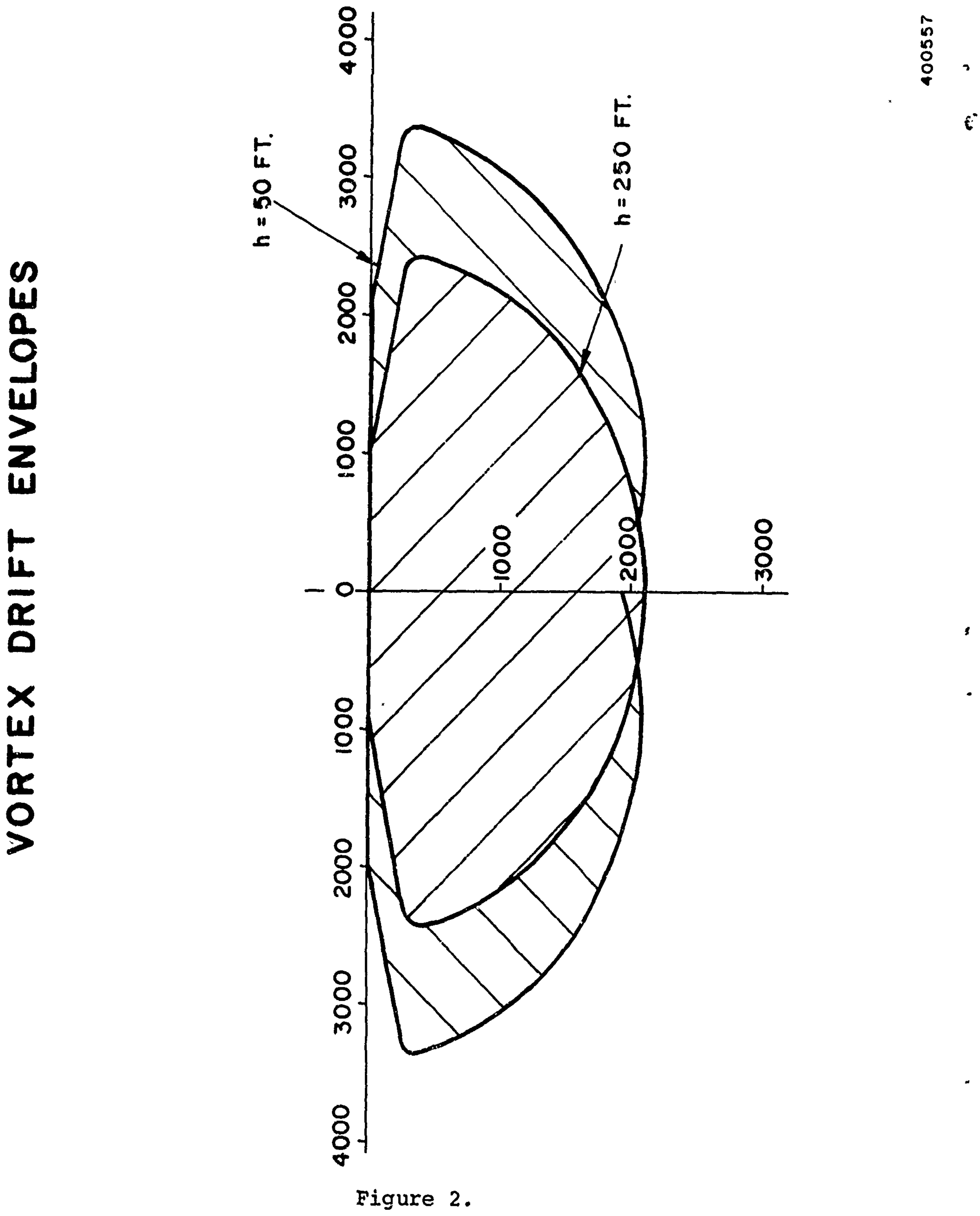

VORTEX DRIFT ENVELOPES
h = 50 FT.
h = 250 FT.
4000
3000
2000
1000
0
1000
2000
3000
4000
-1000
-2000
-3000
400557

Figure 2.

VORTEX DRIFT ENVELOPES FOR OPERATION ON 15L-33L AT LOGAN

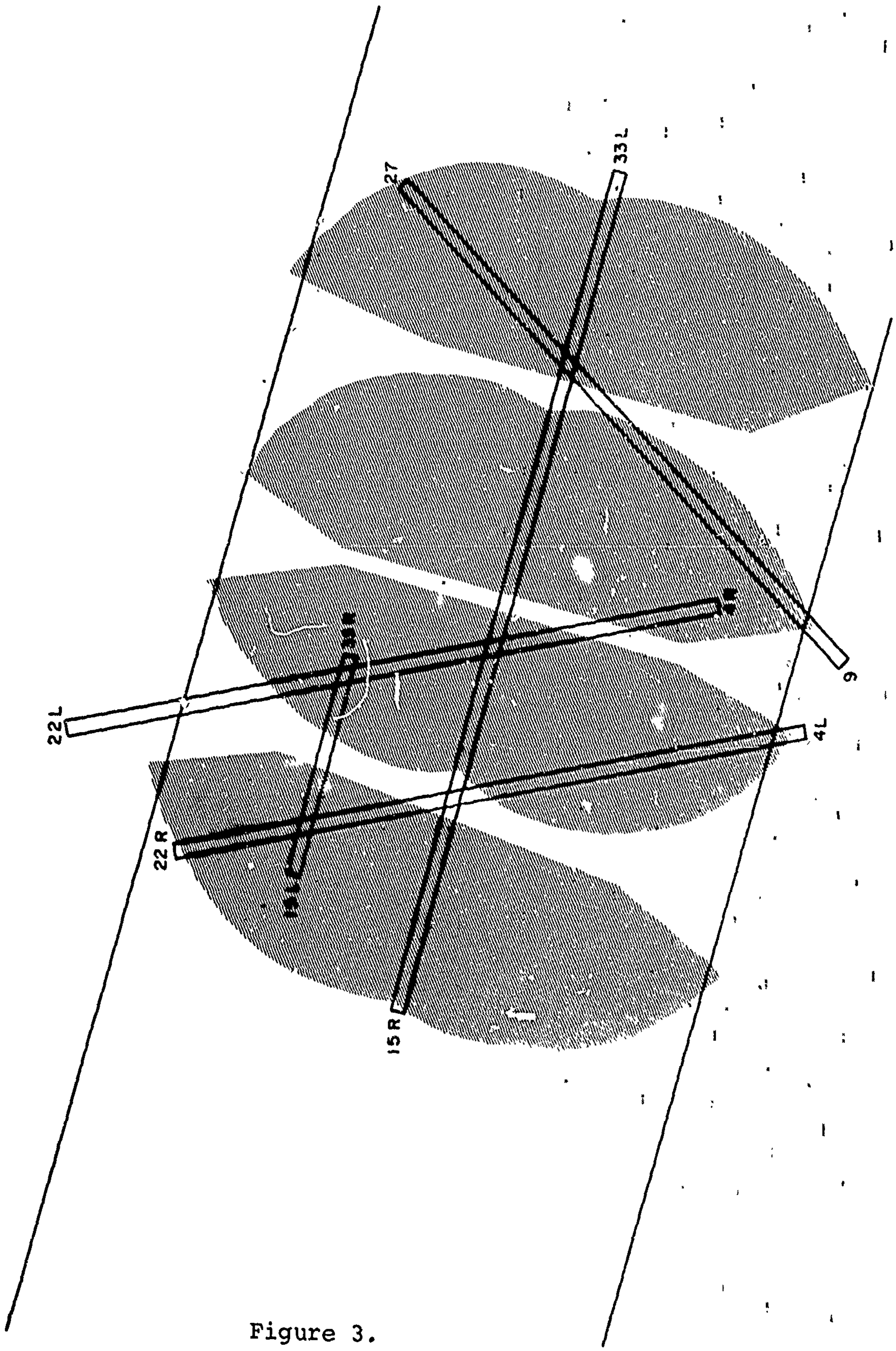
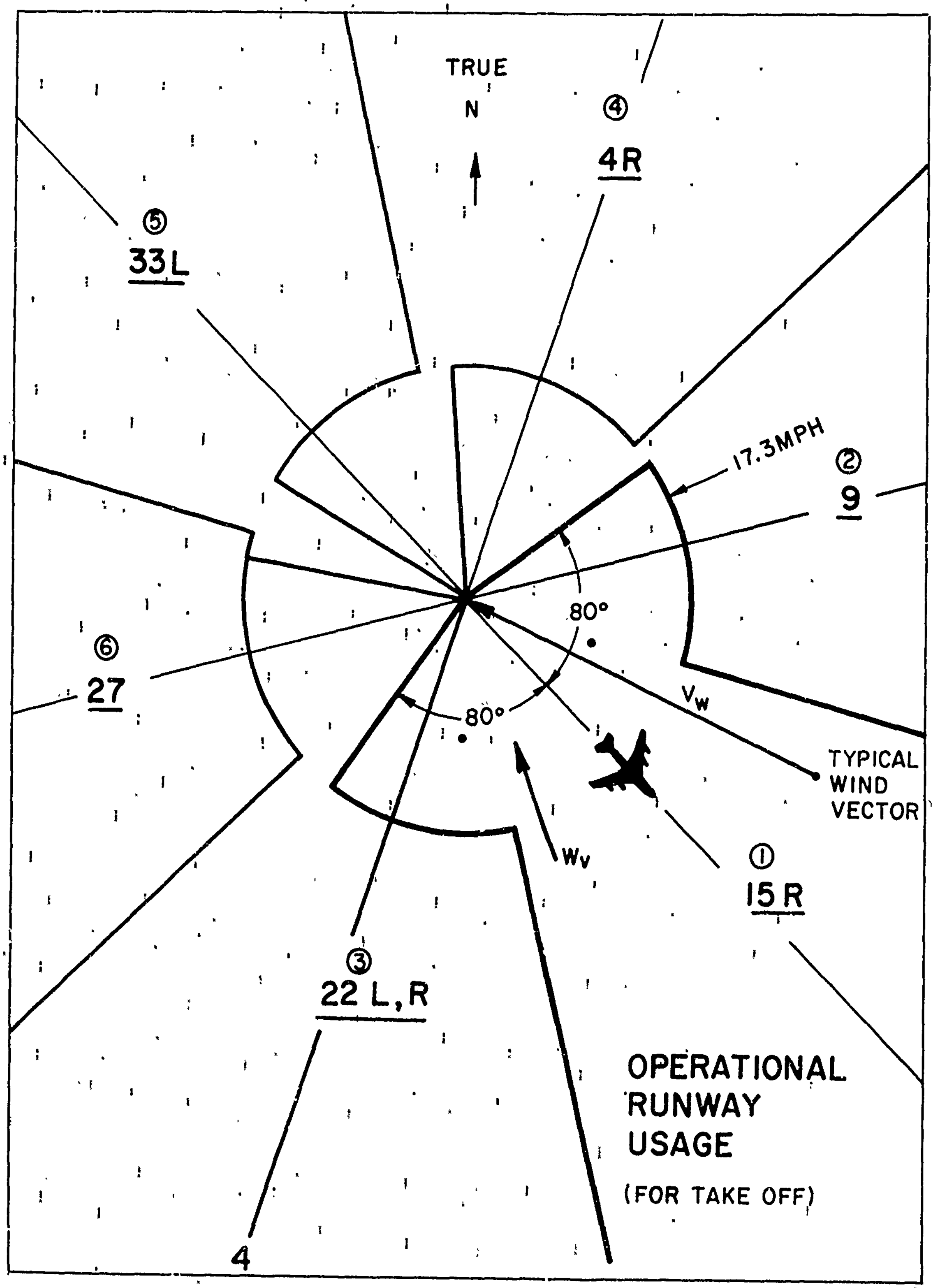
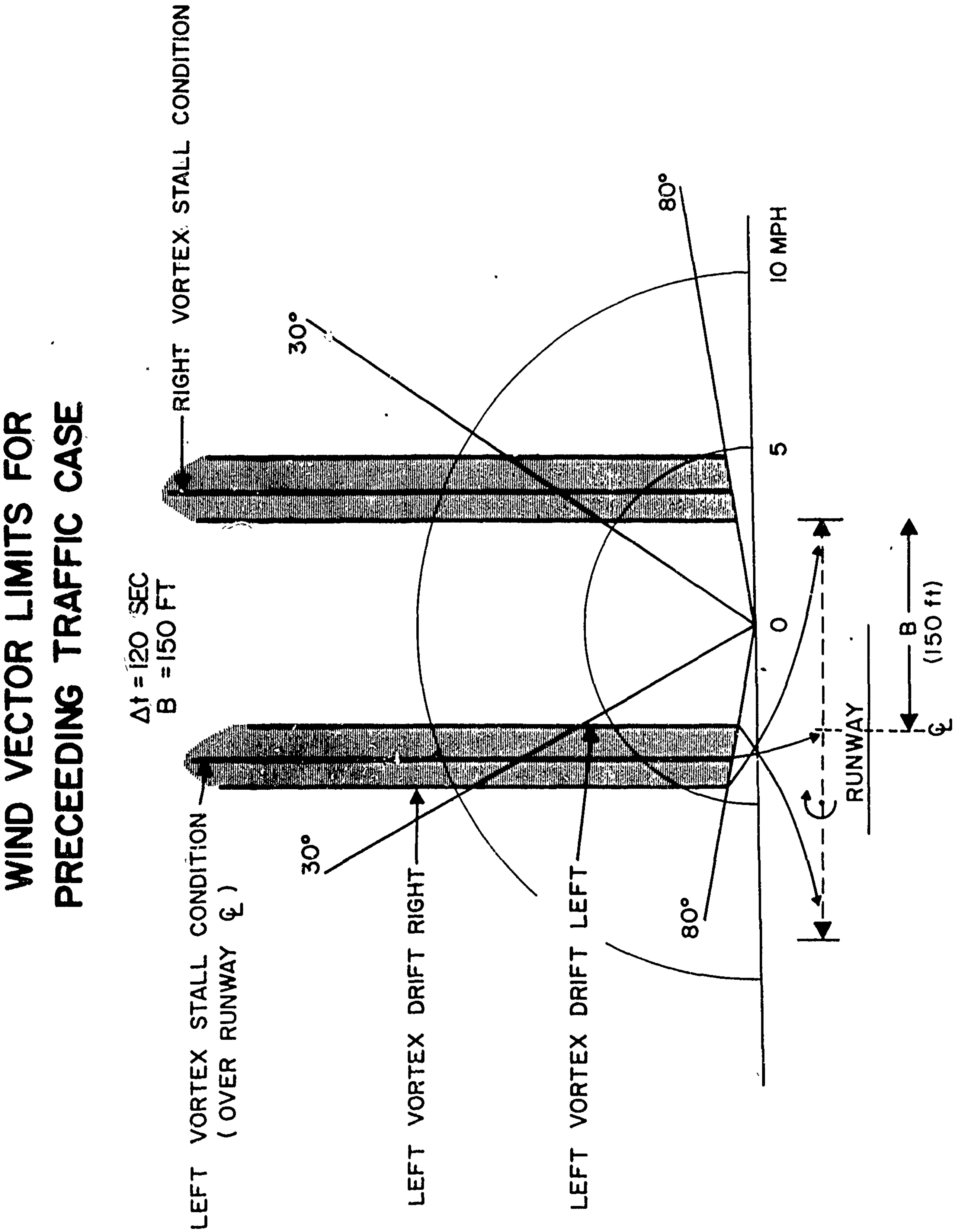


Figure 3.



TRUE
N
④
4R
⑤
33L
17.3MPH
②
9
80°
80°
⑥
27
V_W
TYPICAL
WIND
VECTOR
W_V
①
15R
③
22 L,R
OPERATIONAL
RUNWAY
USAGE
(FOR TAKE OFF)
4

Figure 4.



WIND VECTOR LIMITS FOR
PRECEEDING TRAFFIC CASE
Δt = 120 SEC
B = 150 FT
RIGHT VORTEX STALL CONDITION
LEFT VORTEX STALL CONDITION
(OVER RUNWAY ℄)
LEFT VORTEX DRIFT RIGHT
LEFT VORTEX DRIFT LEFT
30°
30°
80°
80°
10 MPH
5
0
RUNWAY
B
(150 ft)
℄

Figure 5.

PERCENTAGE OF TIME VORTICES AXIS MAY BE FOUND NEAR RUNWAY AS A FUNCTION OF AIRCRAFT SPACING

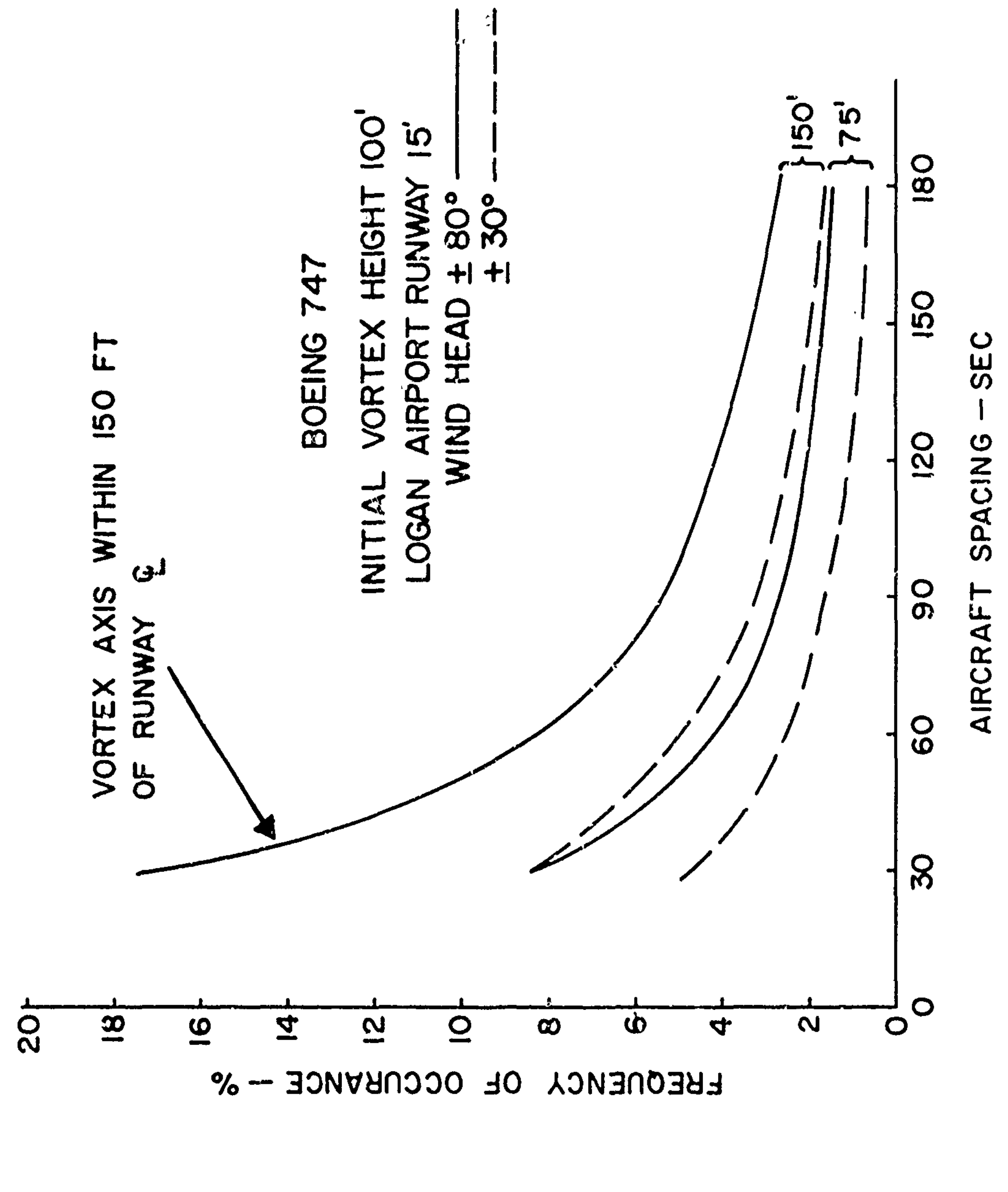
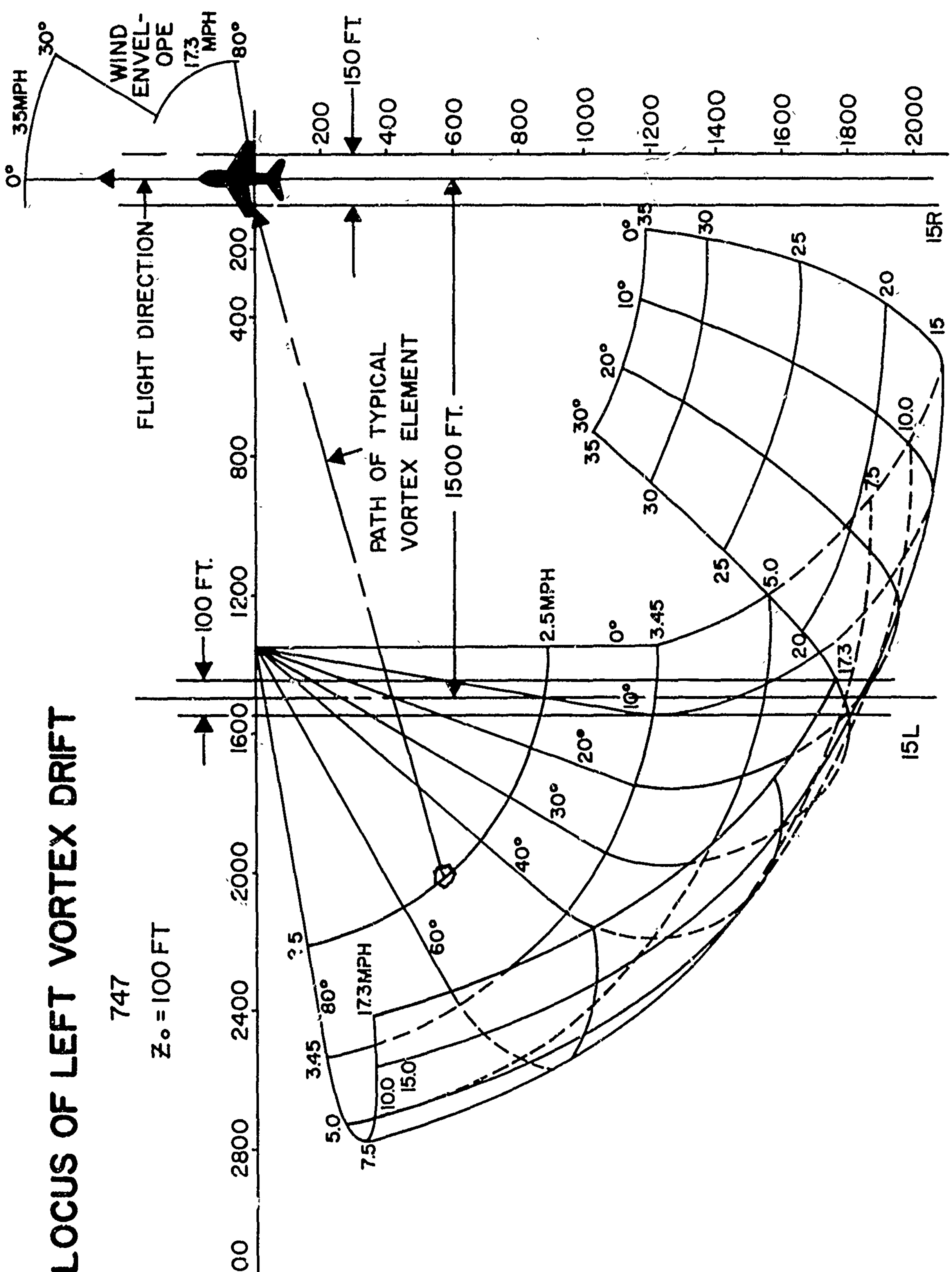


Figure 6.



LOCUS OF LEFT VORTEX DRIFT
747
Z₀ = 100 FT
FLIGHT DIRECTION
PATH OF TYPICAL VORTEX ELEMENT
WIND ENVEL-OPE
35MPH
17.3 MPH
150 FT
1500 FT.
100 FT.
2.5MPH
17.3MPH
15R
15L

Figure 7.

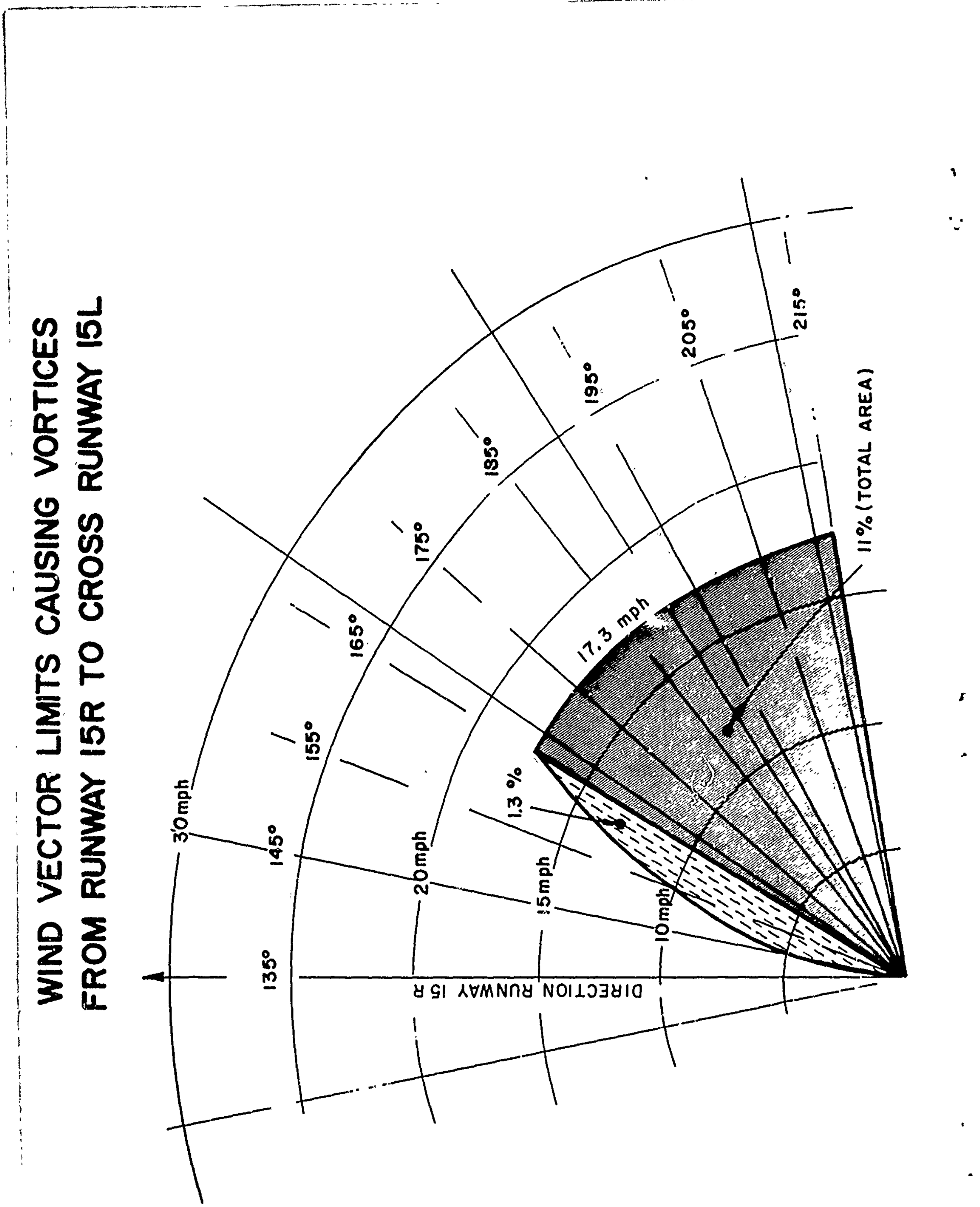

WIND VECTOR LIMITS CAUSING VORTICES
FROM RUNWAY 15R TO CROSS RUNWAY 15L
30mph
20mph
15mph
10mph
135°
145°
155°
165°
175°
185°
195°
205°
215°
17.3 mph
1.3 %
11% (TOTAL AREA)
DIRECTION RUNWAY 15 R

Figure 8.

VORTEX MONITORING REGIONS RUNWAYS, 15L, 15R

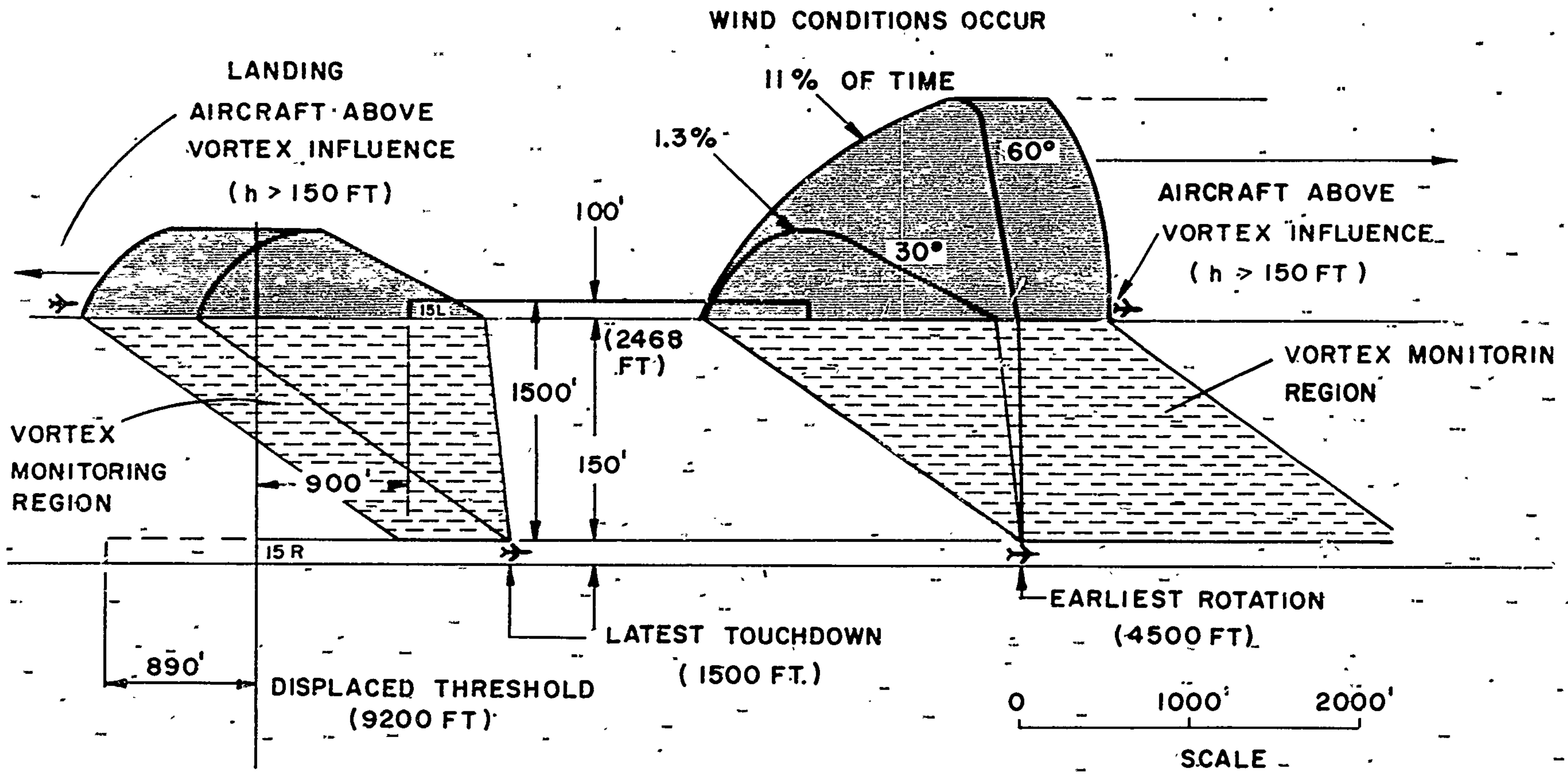


Figure 9.